Dynamic and static cues for binocular vision – a systematic comparison

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy

by

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Contents

Abstract

Dynamic and static cues for binocular vision – a systematic comparison.
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Background
Patients who are diagnosed as stereo blind, during clinical assessment have reported a compelling, volumetric perception of depth during stereoscopic viewing at the cinema. This effect cannot entirely be explained by the monocular cues present in the cinematic presentation. This lead to the theory that depth from binocular cues may be more apparent when motion is included in the scene.
As an object approaches in space is detected through the use of two binocular cues, changing disparity over time, and intraocular velocity difference. These cues have been previously investigated in terms of detecting the presence of motion and discriminating the direction of motion. In this thesis I am to investigate the contribution of stereomotion to the detection of depth.
Methods
A four alternate forced choice adaptive staircase presentation paradigm was used to assess the ability of participants to detect which of four random dot patterned stimuli patches appeared closest to them in space. The outcome measure for every experiment was depth detection threshold. The experiments were presented using either linear polarised or dichoptic stereoscopic display methods.
The stimulus patches were designed to only define depth through binocular disparity, with care taken to avoid any monocular cues. The target patch was identical to all other stimuli patches other than variations to test the following dynamic characteristics: z-location change, X-location change, changing disparity only, interocular velocity difference change only and changes in pattern. These were all comparable to a static condition, where depth was defined by disparity only. All z-axis (or depth) changes were defined by 'on-screen' separations of half images (the images separated to the left and right eyes in turn). A number of control experiments were also included to assess the effect of fusional demand, of spurious temporal correlations, of variations in speed of changes in depth and of cue construction on depth detection thresholds.
Results
410 subjects were assessed, (aged mean (SD) age 21(5) years) across all experiments. In comparison to the static disparity conditions (415”), depth detection thresholds were statistically significantly lower for the stereomotion conditions, with (CDOT 360”) and without (Z-LOCATION CHANGE 310”) pattern change ($p<0.001$). The presence of a changing pattern in isolation ($p=0.71$) (STATIC PATTERN CHANGE 410”) or a horizontal shift ($p=0.41$) (X-LOCATION CHANGE 420”) did not significantly affect the thresholds. The presence of fusional demand or spurious temporal cues did not cause any statistically significant change in thresholds ($P>0.05$).
Conclusion
The threshold for detecting depth in stimuli that contain z-motion, is better (lower) than for static stimuli, providing an explanation for the experience of compelling depth at the cinema. As z-motion depth detection thresholds were significantly

lower than static thresholds, this suggests motion provides an advantage to extracting depth, above serial static disparity detection alone. The assessment of stereoacuity should include the measurement of depth detection thresholds using changing depth stimuli, in order to fully investigate binocular potential.

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Abbreviations

‘	Minute of arc
“	Second of arc
2D	Two Dimensional
3D	Three Dimensional
3DTV	Three Dimensional Television
AFC	Alternate Forced Choice
CDOT	Changing Disparity Over Time
fMRI	Functional Magnetic Resonance Imaging
HD	High Definition
IOVD	InterOcular Velocity Difference
LE	Left Eye
MID	Motion In Depth
MST	Medial Superior Temporal
MT	Middle Temporal
PC	Personal Computer
Randot	Random Dot (occasionally referring to the preschool Randot stereoacuity test)
RE	Right Eye
SD	Standard Deviation
VA	Visual Acuity
VDU	Visual display unit

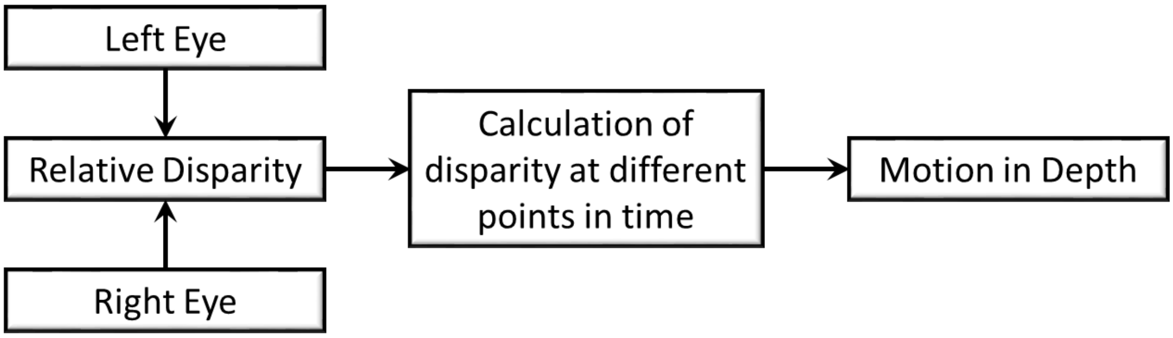
Chapter One - Introduction

Motion in depth

There are two mechanisms that result in the perception of binocular motion in depth. These are Changing Disparity Over Time (CDOT) and Interocular Velocity Differences (IOVD). These are outlined in figure 1.1. The mechanism that detects changes in the amount of disparity over time (CDOT), relies on the interpretation of changes in the separation between any spatially corresponding points in the right and left eye. A CDOT stimulus is perceived as movement through depth (z-motion, i.e. motion towards or away from the observer) through the recalculation of disparity and recognition of a change in disparity over time, providing information on changing depth. The second putative mechanism extracts the interocular velocity difference (IOVD) between the two eyes. The IOVD mechanism does not require spatially matching points between the two retinas; rather it utilises motion of individual points across each retina separately, and the difference in velocity between the two eyes is used to infer depth (Figure 1.3). For example, an object which moves straight towards an observer will result in rightward retinal motion in the right eye and in leftward motion in the left eye. Comparing these two velocities is informative about the change in depth of the object.

While there is evidence for two distinct mechanisms processing these cues (CDOT and IOVD), (1-7) under natural viewing conditions these two cues are unlikely to occur in isolation and performance is better when both cues are present. The more robust cue for the extraction of motion in depth tends to be CDOT, (1,2) with only small subsets of individuals able to use the IOVD cue in isolation. (2,3)

a.



b.

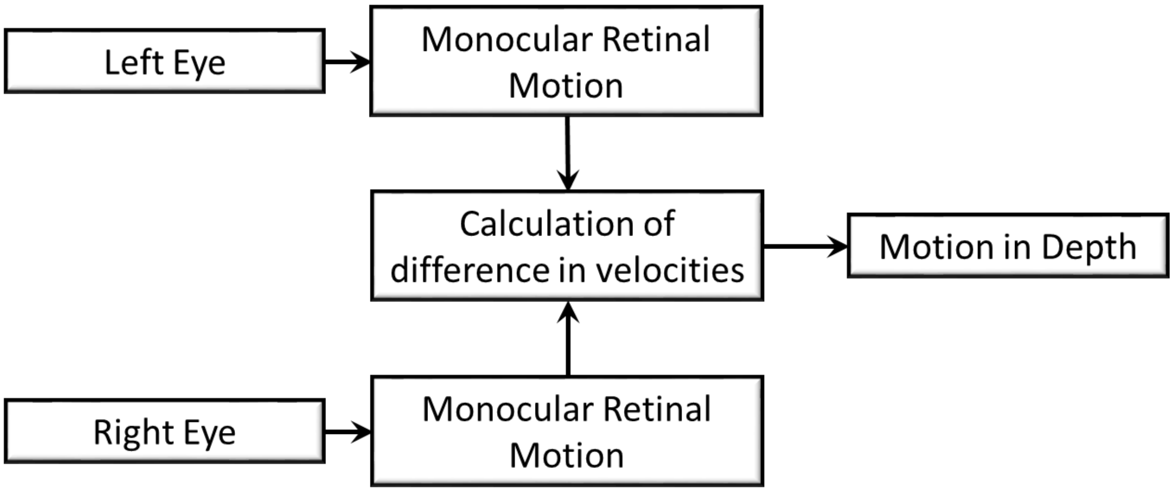


Figure 1.1: a. A flow chart of the CDOT mechanism. The relative spatial disparity of a stimulus is determined, and recalculated at successive time intervals. The successive changes in disparity provide the cue to motion in depth. b. A flow chart of the IOVD mechanism. The speed and direction of the motion of a stimulus across each individual retina is first determined. If these disparate motions are determined to originate from the same stimulus, the difference in velocities are perceived as motion in depth.

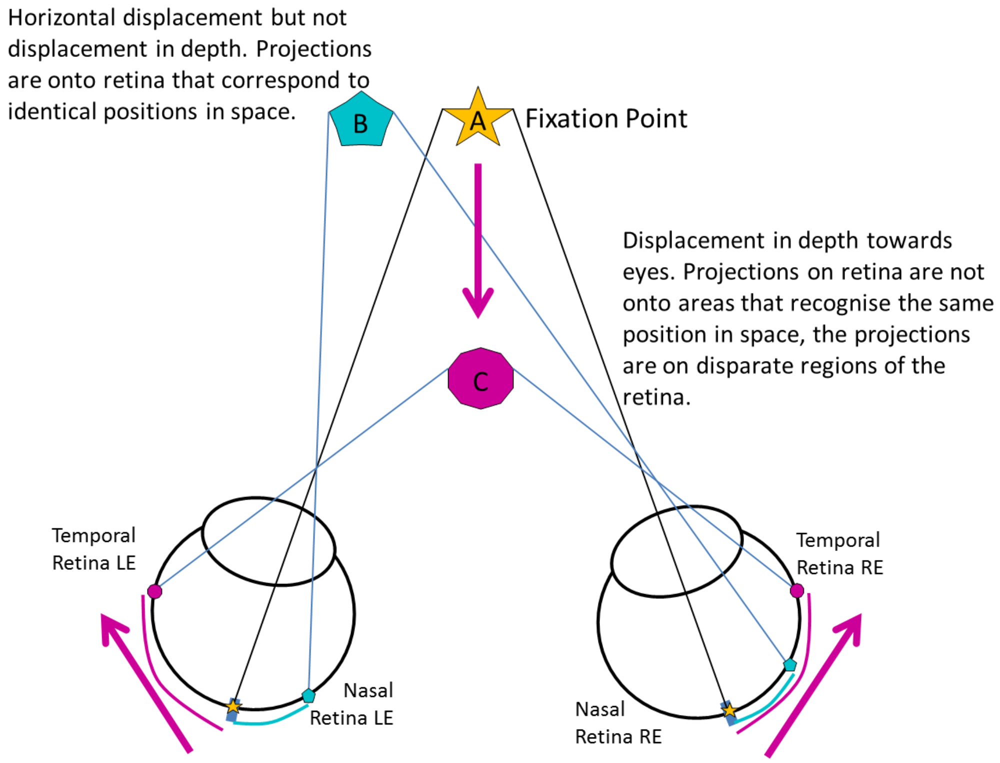


Figure 1:2: Diagram of disparity change. At the object 'C' moves towards the eyes, its binocular disparity increases, as its position on the retina changes. The purple arrows show direction of motion of the real object and the projection of the object on the retina. The replication of this motion in an IOVD stimulus, reasons that the stereoacuity threshold attributed to an individual for recognising the binocular disparity at this point, can also be used to describe the ability to recognise the IOVD cue to depth moving across the same amount of retina. The arrows and arcs show the perceived motion based on the motion across each retina.

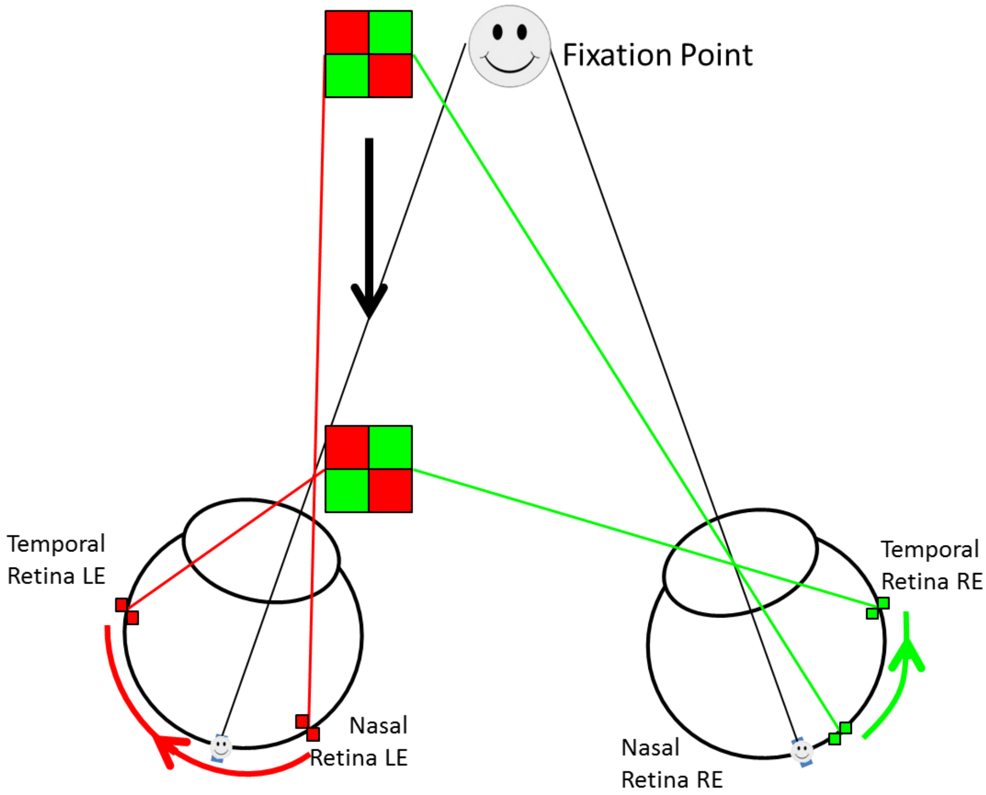


Figure 1:3: Diagrammatic representation of the IOVD cue. The non-spatially-corresponding points undergo differing motion across each retina. The red elements of the stimulus have further to travel and therefor move at a greater speed – the velocity is greater. In contrast the velocity of the green elements is smaller, moving in the opposite direction, at a slower speed. The difference in velocity between the motions across the retina are interpreted as motion through depth: the object is perceived to approach the observer.

The detection of depth, with changing depth

There are surprisingly few studies that have directly considered the detection of depth in moving stimuli, as the majority of studies consider the perception of direction of motion in depth. Individuals tend to perceive a greater amount of depth in stimuli that move through depth. When asked to match the amount of depth apparent in an approaching stimuli to a static target in depth (communicated by changes in disparity/interocular velocity differences), participants consistently matched lower amounts of disparity in the stereomotion stimuli, to stimuli with static disparity. That was a statistically significant trend to reporting a depth match before the approaching target contained as much disparity as the static target. In other words, observers perceived the changing depth stimuli as closer than would be predicted by the magnitude of image disparity. (8)

An early experiment demonstrated that targets which are difficult to locate can be found more quickly and with fewer errors and misses in the presence of stereomotion, than with comparable fixed/static disparity presentations. (9) The capturing and display of the stereoscopic content was a complex procedure, using a film camera and projectors, and motors oscillating the capture camera. The outcome of the capture procedure resulted in a right and left half image, that were 180^{o} out of phase. When displayed to each eye individually using polarising filters, the percept was of targets moving toward the observer. The time taken for the participants to identify a number of targets was assessed with a fixed amount of disparity (no motion) and with induced stereoscopic motion and showed that the time taken to identify stereoscopic targets is significantly lower when the targets undergo stereoscopic motion.

A slightly more recent study measured the time taken for participants to determine the closest of four binocular targets with various relative disparities, as they moved on a track through depth towards the participant. (10) The time taken to identify the closest target did not correlate significantly with static stereoacuity scores as measured with either the TNO or Titmus tests. It does appear that levels of performance with moving and stationary targets are unrelated based on these findings, however the differences between stimuli and procedure for the two tasks may compromise the interpretation of results. The stimuli in the experiment were a four-alternate design, but the task was always to determine the difference between the four targets. This relative disparity would never change as the difference was fixed by construction.

The TNO or Titmus fly tests are very different to the ‘real’ contour stimuli used on the experimental apparatus box (similar to the Frisby Davis 2 stereotest, with one shape closer than the others), which approached the subjects on a rail. There is no detail regarding fixation instructions, and so it is likely that the subject would have tried to pursue the target binocularly, probably making substantial vergence errors. (4) It's likely that for a presentation of several seconds, a number of corrective vergence saccades would have been made. This would result in absolute disparities presented during the experiment being very variable, presenting large disparities, and not the fine 2 arc second disparity the authors claim.

Stereoacuity is traditionally considered as the threshold measure of how well an individual can interpret binocular disparity as perceived depth, by determining the spatial correlation of points projected onto the retina. Zero disparity is when the image is at the fixation point and projects onto corresponding points of each retina, either on both fovea or on corresponding points of the temporal and nasal retina in the alternate eye.

As a real object moves towards or away from an individual, a number of factors change, including a number of monocular cues, and two binocular cues to depth. Any point forward of where the eyes are fixated provides crossed disparity, that is, these points are projected on the temporal retina of both eyes. This is binocular disparity, as the corresponding point to the temporal retina of one eye, is the nasal point of the other eye (figure 1.2 shape "c").

As the amount of disparity of an object moving through depth changes, the image of the object moves across the retina over a period of time (the time of the objects movement) (figure 1.2). Within this motion across the retina, two cues to depth are inherent. Firstly, there is a change in the amount of disparity between each eyes retina (changing disparity over time (CDOT)) and second, a synergistic movement of the image across the retinae in opposite directions or differing speeds (interocular velocity difference (IOVD)). In order to isolate the CDOT cue, motion of the points across the retina over time must be removed, and to isolate the IOVD cue any spatial correlation must be removed (separate points of square in figure 1.3).

To present the changing disparity over time cue, each time a new disparity is presented, a new set of spatial correlations must be presented. To present an interocular velocity difference cue, no spatial correlations should be present at any time, only the motion across the retina.

To portray a depth of 300” (seconds of arc) the disparity of the retinal projections differ by 300”. If the object started at zero disparity and moved through depth to 300”, the object moves across an amount of retina equivalent to a disparity of 300” – which if detected, would represent an stereoacuity threshold of at least 300”. Because of this, even though no spatial correlations exist, the elements of an IOVD stimulus can be considered as having 300” of disparity as they have moved across 300” of retina, and therefore represent a stereoacuity threshold of at least 300”.

The detection of motion vs the detection of depth

The purpose of this thesis is to examine the detection of depth in the presence of motion, however, interest in stereomotion detection has been frequently considered in the field.

Sensitivity to stereomotion (the ability to determine the approaching target) has been demonstrated in the absence of measurable static stereopsis in a 46 strabismic patients, with improvements also found following corrective surgery. (11) Fukikado *et al.* demonstrated that 39/52 subjects were able to locate a pattern moving in depth, while only 28 could experience stereoscopic depth of the fly on the Titmus test. (12) Watanabe *et al.* determined detection thresholds for stereomotion in 52 strabismic subjects and found that six were able to detect stereomotion at thresholds of less than 1200”, despite being unable to detect depth in stimuli with 1200” of static disparity on the Titmus test. Conversely four out of the 17 who could demonstrate static stereoacuity of 500” or better were not able to detect the stereomotion stimulus. (13) Of 31 esotropic patients, Maeda *et al.* found that a total of 18 with no measurable static stereoacuity, as per the Titmus fly test, were able to recognise binocular depth from motion. (14) Hess *et al.* demonstrated residual stereoscopic function for stereomotion stimuli in two out of 15 strabismic amblyopic subjects who could not demonstrate static stereoacuity. (15) They further investigated a subsample of four stereomotion blind subjects by placing a neutral density filter in front of their fixing eye, to balance mean-luminance to the amblyopic eye. This enhanced the detection of stereomotion above the chance level previously demonstrated; suggesting consideration should be paid to any visual acuity difference in subjects used for stereoscopic research.

All of these studies demonstrate the potential of subjects with no measurable static stereoacuity to provide a response based on binocular processing when the stimuli contain stereomotion. There are a number of barriers however in previous investigation that does not allow us to be confident that depth detection from stereomotion is superior to static depth detection.

The enhanced perception of depth reported by clinically diagnosed stereoblind subjects, could be attributed to peripheral cues, indeed, further to Kitoji and Toyama's findings in the peripheral visual field, findings in the central visual field show that while 40% of subjects could detect static depth, only 24% were able to detect depth from stereomotion. (16)

Scotomas of stereoblindness to motion in depth vs static depth

When considering the literature on the ability to detect a change in direction of motion, several studies have shown examples of stereomotion scotoma where intact static depth perception is present. This has been demonstrated to coincide in specific areas of a single subject's visual field, though normal performance may be possible in other areas. This 'area' can be either a location in a frontoparallel plane or a range of disparities. (4,17-19) Cases of intact stereomotion perception in areas where subjects are unable to detect differences in static depth have also been presented in the peripheral visual field of strabismic subjects. (11,16) This may account for the enhanced perception of depth experienced by some when viewing 3D entertainment media.

Aim and Summary of experiments

The overall aim of the thesis was to determine if stereomotion allows the detection of depth at a smaller disparity than static presentations of binocular disparity. The recent literature has mostly been concerned with the discrimination of direction of, speed variation in, and the trajectory of motion in depth. This study uses modern psychophysical methods to compare static and dynamic binocular cues to depth, to investigate the advantage of stereomotion to the task of discriminating depth. The stimuli were carefully controlled to ensure that the any advantage were due to binocular, rather than monocular detection of motion.

Chapter three and four concern a systematic investigation of static and dynamic stereoscopic stimuli (experiments 1 (blocked design) and 2 (interleaved design) to determine whether dynamic cues are superior to static cues for depth detection. Chapter six contains a series of control experiments, and looks at the contribution of spurious IOVD cues in the stimulus (exp. 3a), the effect of the varying proportions of CDOT and IOVD cue in the stimulus (exp. 3b) and the effect of varying the rate of change of disparity on depth detection thresholds (exp. 3c). Chapter five investigates the effect of vergence demand on depth detection thresholds in both static and stereomotion stimuli (exp. 4).

Chapter Two - General Methods

The general approach taken for each experiment is described in this chapter, however, some details differ amongst chapters and so the differences are described again in each.

Ethical Approval

Ethical approval was gained from the University of Liverpool Ethics Sub-committee to cover all experiment in this thesis (see Appendix I for approval confirmation). The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki. Participants were recruited from the staff and student population of the University of Liverpool, via advertisement for volunteers to participate in a 3D vision study, through personal contacts and via the electronic participant recruitment system in the school of psychology. Prior to participation, informed consent was gained from each of the subjects.

Screening

Inclusion criteria were broad for all experiments with the only requirement appearing on advertising: 'Vision of driving standard in at least one eye'. This broad criteria was designed to allow the recruitment and assessment of an incident population reflective of the 'normal' population. Combined with the non-specific instruction to 'select the target that appears closest to you', it was hoped to provide a broad indication of whether smaller amounts of depth are detectable in dynamic, over static presentations, in the population. Visual acuity was measured using the Early Treatment Diabetic Retinopath Study (ETDRS) LogMAR chart (Precision Vision^{TM}; La Salle, IL,USA).

Subjects were further assessed upon recruitment (any excluded in chapter 5 if no simultaneous perception was present) to confirm the presence of any grade of binocular single vision. Although not a requirement of participation, all recruited subjects had demonstrable stereopsis of at least 800" on standard clinical testing using the Titmus stereotest circles (Stereo-Optical; Chicago, IL, USA) or Frisby stereotest. This is mentioned to highlight that some subjects were unable to perform the psychometric task reliably, rather than not being able to detect binocular disparity.

There was a second stage of 'exclusion' based on unreliable results. As explained above, some subjects were unable to contribute meaningful results. If this were the case for all conditions in an experiment, these subjects were deleted in a listwise basis. This was determined by the goodness of fit as explained later in this chapter.

Subjects

Across all experiments, a total of 410 subjects were assessed with over 380 of these representing unique subjects. The ratio of female to male participants was approximately 3:1 with ages between 18 and 56 years, mean(SD) age 21(5) years. Though a small number of participants (~5) were experienced in psychophysical experiments the majority were naïve to psychophysics.

The subject pool was recruited from the staff and students and Nuffield summer students of the University of Liverpool through printed advertising, electronic announcements and email calls. No financial inducement was offered for any experiment. All subjects provided informed consent prior to participation, having received the information sheet upon initial contact.

Apparatus

Display Types

A number of stereoscopic presentation options were explored to determine the display of choice for this course of study, with the final decision largely based on cost implications.

The ideal display for stereoscopic research is one where the pixels of the display for the right eye, and the pixels for the left eye are presented in the same spatial location at exactly the same time. The pixels must also be as small as possible to limit the size of changes of disparity, in order to accurately detect a change.

There are four main methods of delivering stereoscopic content currently in use: The first is a Wheatstone stereoscope, where two displays are positioned and reflected using a pair of mirrors to each eye. The alignment of this system can be difficult, especially as due to its close proximity to the observer, interpolation is used to decrease the size of disparity jumps, which makes maintaining perfect pixel alignment vital. The second method requires similar alignment precision, using a pair of projectors incorporating polarising filters to separate the image. This method requires the participant to wear polarising glasses to view the stereoscopic effect. A similar system (a cross between polarised projectors and the Wheatstone stereoscope), with built in stable alignment is the Planar system (appendix II), where a semi silvered mirror is placed between two perpendicular LCD panels and viewed using polarising glasses.

The most common commercially available methods of delivering stereoscopic content are active shutter systems, which allow for perfect spatial alignment, but present a different image to each eye at a different point in time with low end systems commonly resulting in problems with synchronisation between the display and glasses. Another version of the active shuttering is to filter the image being projected to alternate eyes by rapidly changing the orientation of polarising filters positioned in front of a projector and the observers wearing polarising glasses, but synchronisation issues may still occur. Passive circular polarising displays avoid this issue by presenting the left and right half images at the same time, albeit on alternate lines of pixels, introducing an amount of vertical spatial disparity. Autostereoscopic methods are also available which do not require glasses, the use of a parallax barrier prevents each eye from seeing the image meant for the other. Again, the spatial location of corresponding points differ, and a limited 'sweet spot' exists to maintain viewing of the stereoscopic effect. Lateral movement can result in reversal of the direction of disparity, resulting in a large amount of movement through depth.

Display I - LG

VDU Type

The choice of display used in experiments one through three was an LG Flatron D2342, circular polarised passive 3D monitor, 1920 by 1080 pixels, run at 60Hz .

Each alternate line of a passive polarising '3D' screen can only be seen by the corresponding eye when wearing the corresponding 3D glasses (see figure 2.1). Each red, green and blue triplet is one pixel. The black line between each row of pixels is designed to prevent 'cross talk', that is, transmission of the signal meant for the right eye to the left eye (and vice versa).

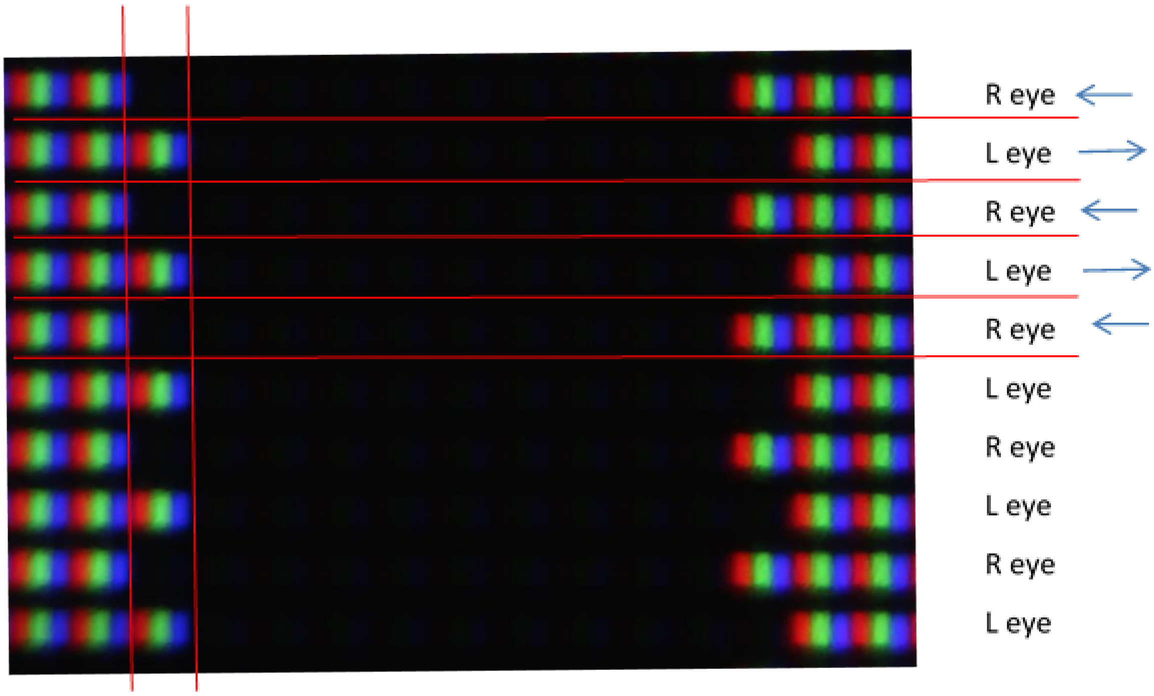


Figure 2.1: Macro photograph of a 10 by 10 pixel black square with one pixel of on screen disparity. Horizontal lines separate left and right eyes, vertical lines show one pixel.

Disparity Calculation

Due to the positioning of human eyes, typically 60mm apart, a slightly different view of the world falls on each retina. Assuming correct ocular alignment, any point forward of the point of fixation produces ‘crossed disparity’ and anything beyond it produces ‘uncrossed disparity’. In crossed disparity the points fall on the temporal retina of the either eye.

Figure 2.2 shows an amount of crossed disparity, by artificially adjusting where the objects image falls on the retina. The fixation point must be the screen plane (backed up by a fixation target), otherwise the image will be blurred. Therefore the image of the black square falls temporal to the fixation point on each retina.

To work out the amount of disparity produced by a shift of the image on screen we need to know two things:

1. The viewing distance (‘a’)

   This was maintained throughout the experiments by aligning the monitor with a mark on the floor, and through the use of a chin rest fixed to a table.

2. The size of the separation on screen (‘o’)

Tan(α) = Opposite (‘o’) over Adjacent (‘a’)

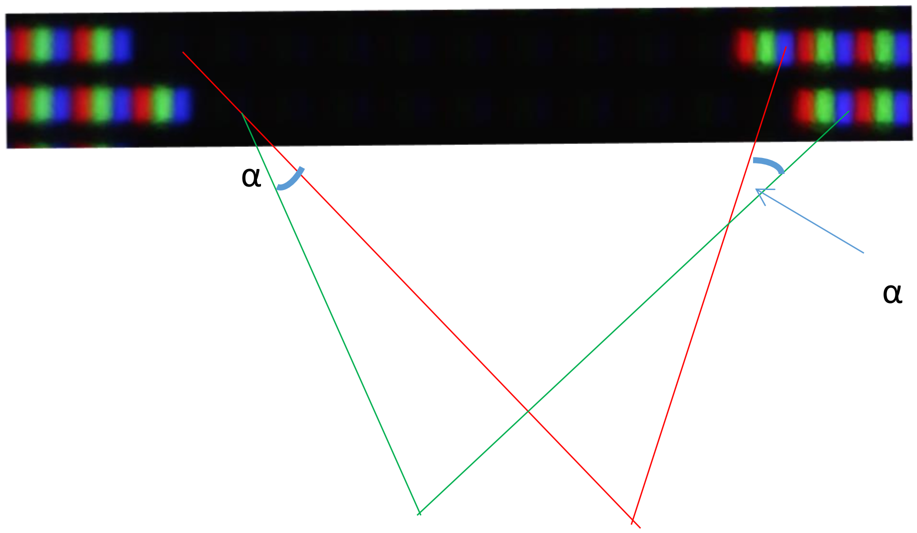


Figure 2.2: Schematic of one pixel of on screen disparity, α is the angle of disparity

To work out on screen disparity the angular size of the difference between the left and right eyes half image must be calculated.

The following requires the presence of a right angle:

$$Tan(\propto) = \frac{Opposite}{Adjacent}$$

To construct the triangle necessary to create a right angle we halve α and 'o' (figure 2.3):

$$Tan(^1/_2 \propto) = \frac{^1/_2\, Opposite}{Adjacent} = \frac{Opposite}{2 \times Adjacent}$$

To determine the on screen disparity in degrees, α:

$$\propto = 2\times \tan^{-1}\frac{Opposite}{2 \times Adjacent}$$

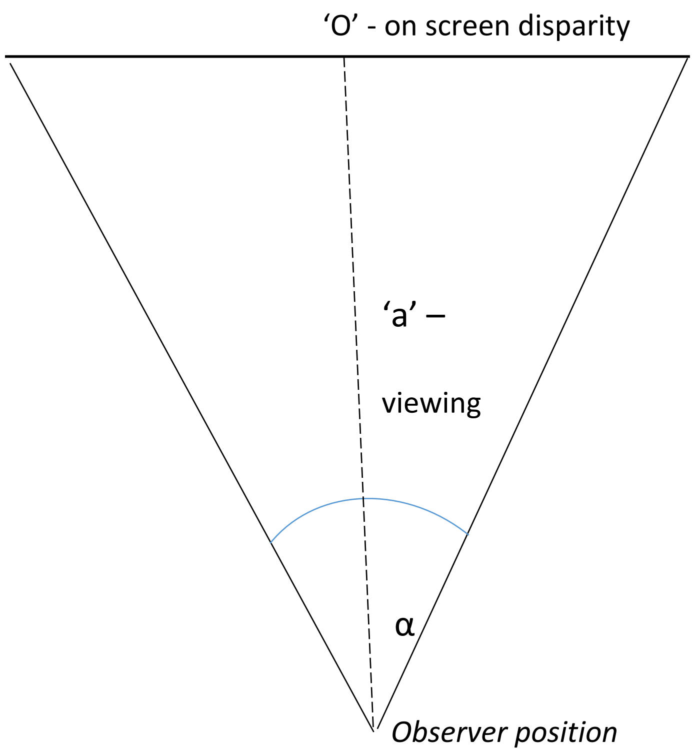


Figure 2.3: Diagram of visual angle

The Flatron D2342 (LG Electronics, Seoul, Korea) has a resolution of 1920 pixels in width by 1080 high, and has a visible screen width of 0.505263m. The typical viewing distance used in the experiments is 3m which, for one pixel, gives a disparity of 0.005° or 18.09”. One arc second is 1/3600th of a degree.

Cross Talk

A further difficulty with single projection/monitor displays such as passive polarisation and shutter glasses is the potential for cross talk, where the image meant for the left eye is not extinct from the right eye, resulting in a ghost image in the right eye.

To determine the amount of cross talk endemic to the display the luminance of a grey field was measured, to determine if using a high or low brightness setting would result in more or less cross talk. The contrast between the ‘ghost image’ and the intended image can provide an indication of how apparent the cross talk may appear.

A large grey patch (1920x1080 pixels) was programmed to be presented to the right eye only when viewed through the passive circular polarising glasses. The background was black and this was presented to the left eye when viewed through the passive circular polarising glasses.

The luminance measurement function of a Spectrascan PR670 was used to measure the luminance of the display though each lens of the polarising glasses in turn. The

Spectrascan was set up 0.5m from the display on a tripod, with a further stand used to support the polarising glasses in front of the Spectrascan aperture. Both were aligned vertically with the centre of the screen.

Michaelson Contrast would appear to be most appropriate methods for calculating the contrast of cross talk, as the right half image should be half the total of the image feature in a grey patch shown on a black screen to one eye only.

$$\frac{luminance\ max - luminance\ min}{lumiance\ max + luminance\ min}$$

Weber Contrast is more appropriate for features on a uniform background, such as logMAR letter on a white chart, or the stimuli used in these experiments on a grey background.

$$\frac{luminance\ feature - luminance\ background}{luminance\ background}$$

Optical crosstalk (C) is defined by Pala *et al.* specifically for assessing cross talk on 3D dispalys, as follows:

$$C = \frac{L_G - L_{BL}}{L_M - L_{BL}} \times 100$$

Where L_M = Luminance of main image, L_G = Luminance of crosstalk image, L_{BL} = LCD background luminance (20)

High Brightness (Screen setting @100)
Luminance without glasses Grey: 36.61 cd/m^2
Black Level: 0.29 cd/m^2
Luminance through right filter: 27.24 cd/m^2
Luminance though left filter: 1.51 cd/m^2

Michaelson Contrast: 10.50
Weber Contrast: 5.64
C=4.53%

Low Brightness (Screen setting @0)
Luminance without glasses Grey: 15.38 cd/m^2
Black Level: 0.12 cd/m^2
Luminance through right filter: 11.56 cd/m^2
Luminance though left filter: 0.71 cd/m^2

Michaelson Contrast: 11.67
Weber Contrast: 6.14
C=5.16%

The amount of optical crosstalk (C), is counterintuitively lower in the high brightness setting, confirmed by the contrast ratios. The high brightness setting was used for all experiments.

The final experiment was carried out using a modified synoptophore – which is a clinical version of a wheatstone stereoscope that allows the angle of the mirror elements to be independently changed. In clinical use this is a useful feature in that it allows the assessment of binocular potential in those patients with deviation of ocular alignment. The ability to adjust the angle of the mirrors also allows assessment of fusional reserves. A schematic of the traditional synoptophore is shown in figure 2.4.

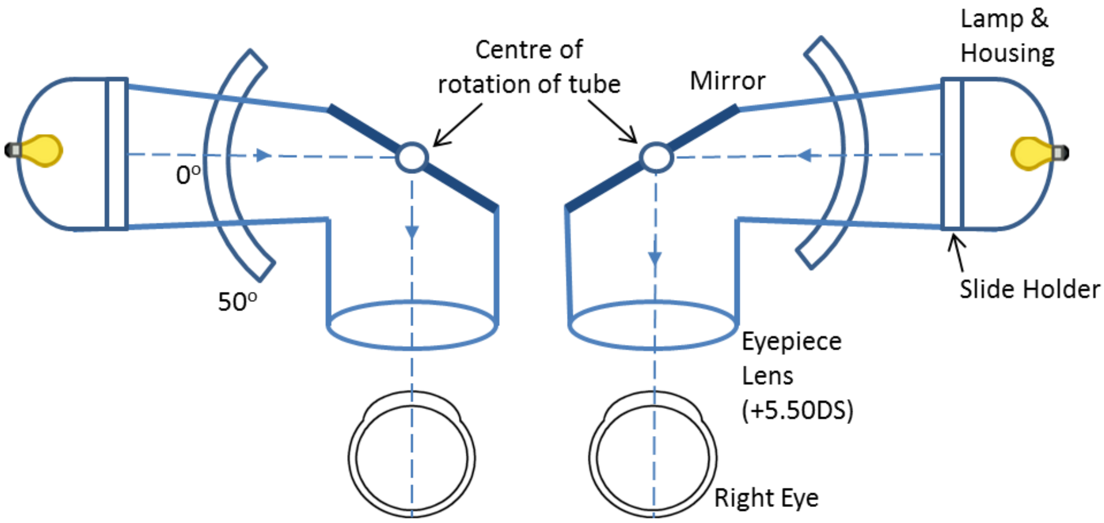


Figure 2.4: Schematic of the traditional synoptophore.

In conjunction with mechanical engineering, modifications were made to allow digital screens to be fitted to the end of the synoptophore tubes in place of the traditional lamp and housing for the glass slides that held the image (see figure 2.5). As each half of the synoptophore is designed as a mirror image of the other, alignment of the device is stable. The slide support plates were removed and symmetrically drilled to allow attachment of the screens. Between the slide support plates and screens, a metal mount was machined to mount the screens. These mounts encompassed a micrometre adjustment mechanism, one in a horizontal configuration and the other vertical. This level of adjustment allowed for perfect pixel adjustment to correct for any misalignment within the manufacturers housing for the display screens.

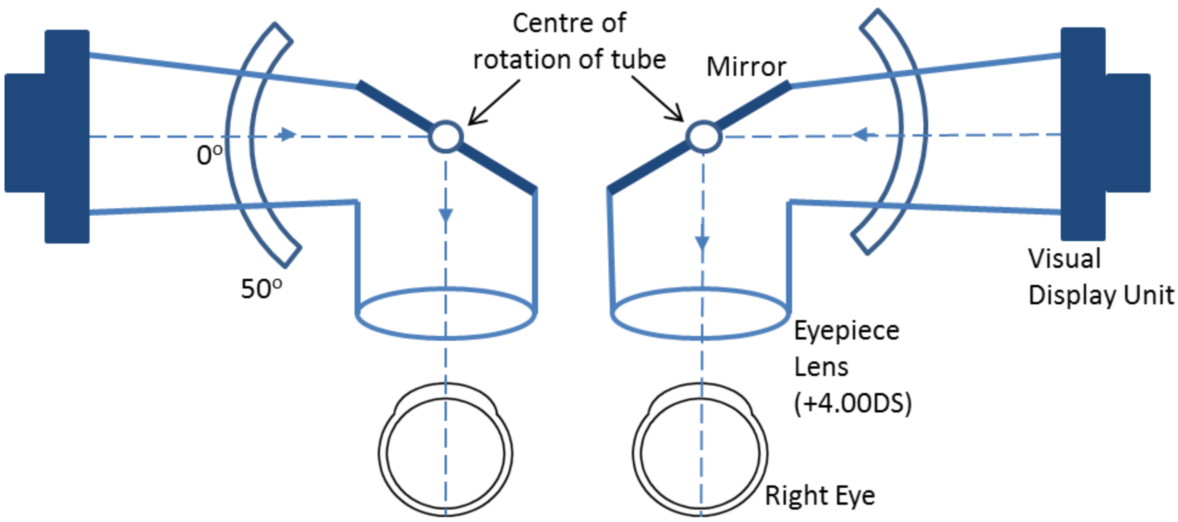


Figure 2.5: Schematic of synoptophore with VDU added to each tube. Note that the eyepiece lens strength has changed.

As the distance from the eye to the stimuli has increased, the eye piece lens must be adjusted to correctly focus the eyes on the screen, without the need for accommodation. Typically lenses are used to converge or diverge light to a specific point. This is especially useful for correcting refractive errors, where light is either to weakly or strongly focused.

In myopia the eye is too large, light is focused too strongly and so does not fall on the retina, rather it focuses in front of it, in the vitreous – thus causing a blurred image. To gain a sharp image the light rays entering the eye are diverged by a concave lens, weakening the focusing power and moving the focus from the vitreous back onto the retina (figure 2.6).

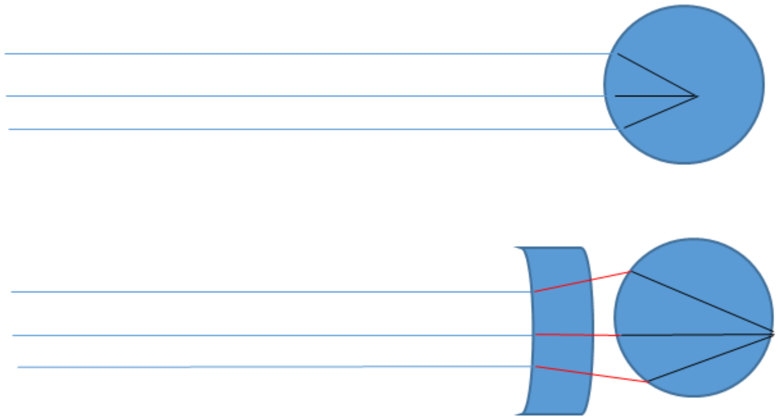


Figure 2.6: Myopic eye

In hypermetropia the opposite is true, the eye is too weak to focus light on the retina, and so, objects are focused somewhere beyond the retina, somewhere in the orbital cavity. To correct this, convex lenses are used to converge the light back onto the retina (figure 2.7).

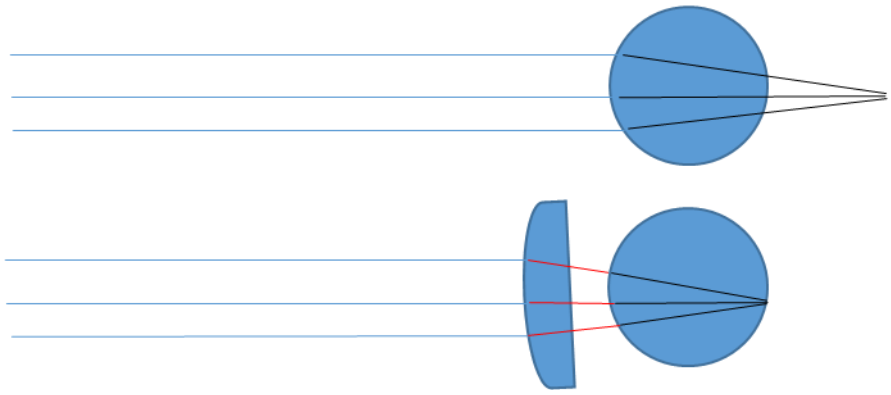


Figure 2.7: Hypermetropic eye

Because P=1/f. The power of a lens (in dioptres) is the reciprocal of the focal length (in metres), and the focal length of a lens is the reciprocal of the lens power.

The eye is designed to focus parallel light sharply on the retina. In the 'non-defective' eye – or corrected to non-defective, under non-accommodative conditions, parallel light will fall on the retina and form a clear image. The optics of the eye matches the focal length, from the front of the cornea, to the retina.

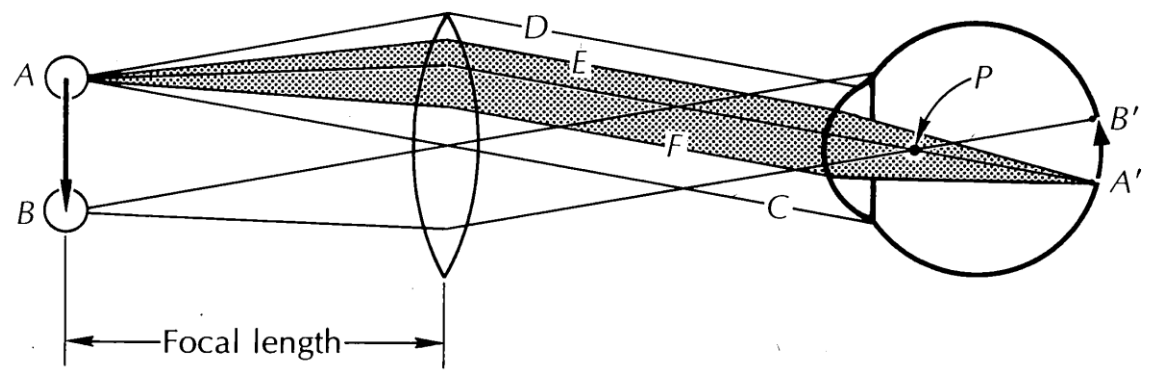


Figure 2.8: Image from 'Visual Perception' by Tom N. Cornsweet, Academic Press 1970

The inverse of this is that a point on the retina will appear in focus in the non-defective eye, with relaxed accommodation, as the light emerging from the eye will be parallel / focused to infinity. Similar to this, if a point is placed at the focal point of a lens, the point will be placed at optical infinity, and so the light from the screen will enter the eye as parallel light. The lens collimates the light coming from the point, making the rays of light parallel (Figure 2.8).

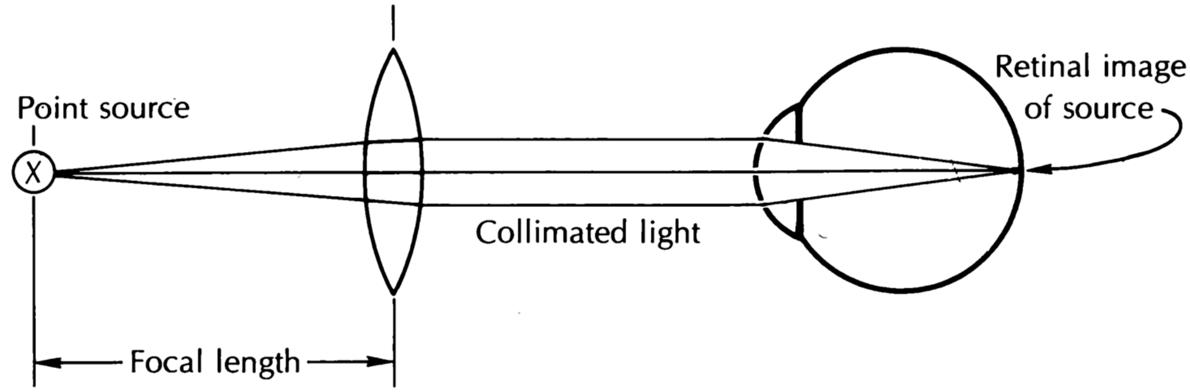


Figure 2.9: Image from 'Visual Perception' by Tom N. Cornsweet, Academic Press 1970

Viewing an 'object', rather than a 'point' means that all light coming from the object which passes through a lens cannot be parallel. However all of the light coming from the object is collimated. That is, the image of every point has light focused to parallel, and so the complete image is perceived as if it were at infinity.

No matter where the object is viewed through the collimator lens, the image will be in focus. The only variation will be the amount of the object visible.

In view of the synoptophore, the device is designed to place the eyes in primary position (no convergence or divergence), the eyes are positioned parallel to each other, focused at a viewing distance of infinity (tubes spaced at the individuals' inter-pupillary distance). As the glass slides are only 18.18cm from the aperture of the viewing tubes, a lens must be used to place the image at optical infinity . A +5.50DS has a corresponding focal length of 18.18cm, and so all light which passes through this lens is collimated. An optically infinite viewing distance is therefore achieved.

By attaching digital screens to the synoptophore, the distance of the image from the aperture is increased to 25.5cm and so the lenses power is decreased to +4.00DS to achieve collimation. No matter the viewing distance from the aperture, light is focused, hence the ability of the camera, as seen the photo below (figure 2.10), to capture the screen contents, whilst the device is in focus.

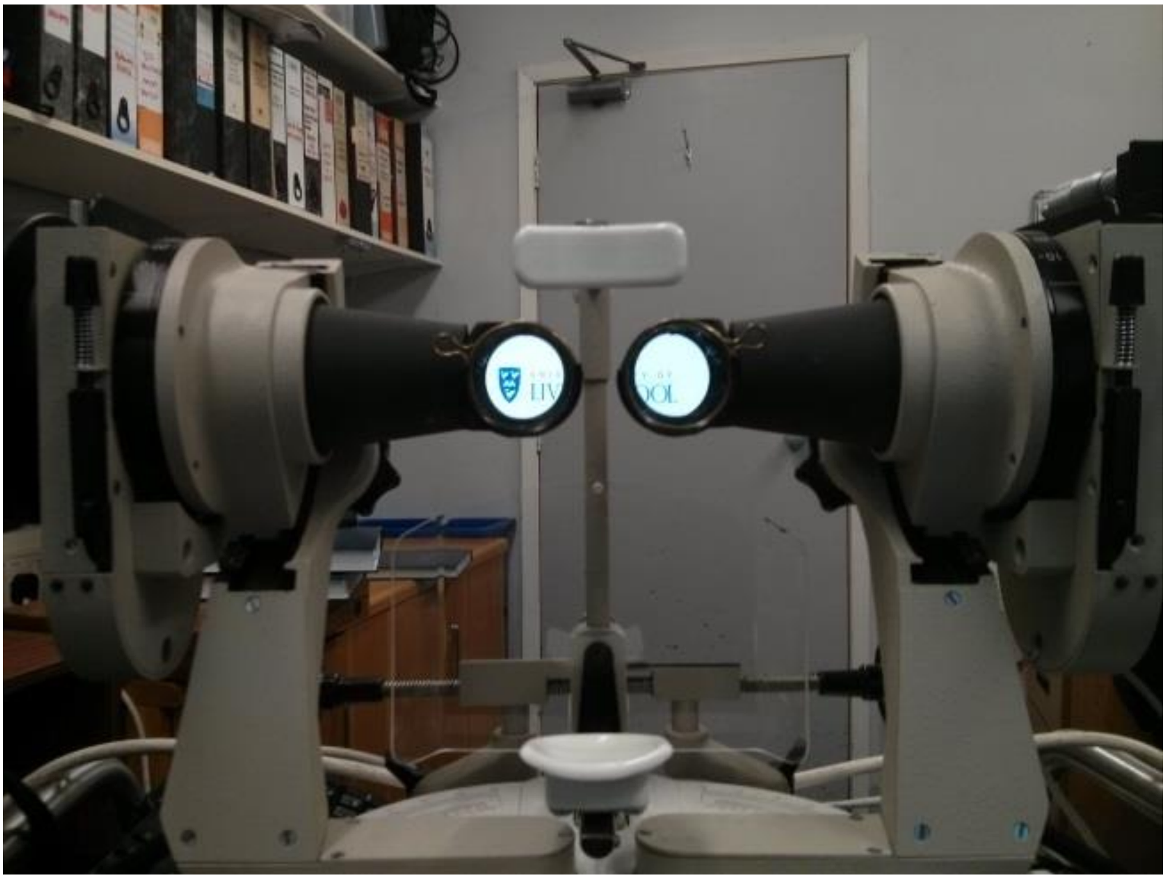


Figure 2.10: Photograph of modified synoptophore, demonstrating collimation of light in the left tube, the image is clear and non-magnified, whereas the stronger lens in the right tube has magnified and blurred the image.

VDU Type

The choice of digital screens used for the synoptophore were a pair of FreeWorld 56D120175 Camera Field Monitors. These monitors were mounted on a synoptophore. The resolution of these monitors was 1280 pixels horizontal by 800 pixels vertical run at 60Hz. Disparity is calculated as above, using the screen width of 0.12065m and a horizontal pixel number of 1280. The viewing distance was 0.225m.

Cross Talk

Zero crosstalk is present when viewing the stimuli on the synoptophore. The left and right image as displayed on physically separate visual display units with no common optics. The effect of crosstalk could be established by comparing thresholds achieved by both display methods.

Development of Stimuli Patches

The stimuli in all experiments were near identical and consisted of a pattern of black dots presented on a grey background. These stimuli patches were precomputed using Matlab (Mathworks®).

The script was used to create a nominal 'square' grid of ten by ten, with the 25 stimuli dots defining the square, with the background consisting of grey. A total of 60 stimuli patches with randomly distributed dots were produced. The decision to use random, rather than uniformly randomly distributed dots across the 10 by 10 grid was made in an attempt to avoid the patch being clearly defined as a square, to minimise contamination of the CDOT cue with the IOVD cue, where the implied edges could provide a temporally correlated edge. The basic script for the development of the stimuli patches is in Appendix III.

In experiment 3a, the stimuli were further developed to remove any chance of spurious IOVD signals occurring within the CDOT stimuli (see chapter 6a). In experiment 6c, where varying proportions of the IOVD and CDOT cue were presented at the same time, the patches were modified to allow overlapping of the stimuli patches (by creating a transparent background instead of grey), with controls to prevent any unwanted CDOT and IOVD cue contamination (see chapter 3c).

Control of experiment

Equipment

The experiments were run using a Pentium i3 windows PC (HP Compaq 8300 Elite SFF) with a clean install of Windows 7. All background process were disabled (windows updates etc.) and no additional software (antivirus etc.) were installed other than Psychopy (21). The standard dual display AMD Radeon HD 7450 (1GB) graphics card was initially used when designing the experiment, but this was upgraded to an NVidia Quadro FX4600. As the small form factor PC could not accommodate this graphics card, the PC was removed from its case and installed into a new housing, with a PCIe extension used to connect the graphics card. The power supply was also modified to accommodate the additional power demands of the graphics card.

Software

Psychopy was employed to take advantage of experimental psychology specific psychophysics libraries.

Stereoscopic display methods

The first attempt at displaying the half images to the appropriate eye was performed by applying a mask to the stimuli patches. The mask consisted of 540 lines of grey, and 540 lines of 'transparency' either starting with a black line for the right eye or transparent line for the left eye. These lines correspond to the number of vertical lines on the HD screen (1080). By applying the mask to the same image, it was possible to display the intended part of the image to the appropriate eye. By offsetting the images horizontally, disparity was introduced, which was perceived as depth by observers.

This method led to lag in the display of images, and was difficult to implement for non-static stimuli. It was also specific to horizontal full HD interleaved screens.

The use of a 'quadro' graphics card (with four buffers) offered a solution to these problems. The quadro graphics card consists of four buffers; right and left front and right and left back, which simplifies the code (using win.setBuffer('right'[/'left'])), as the draw commands can be directed to either the right or left buffer accordingly. This method also allows the script to be run on different displays, as the display type is configured in the graphics card settings, e.g. horizontal interleaved for the LG display and DualDisplay for the synopthopre display.

The Nvidia Quadro FX4600 graphical processors used in the experiments were purchased second hand from eBay, due to financial considerations.

Experiment control

The stairhandler function of psychopy was used to control the initial experiment where the conditions we run in a blocked format. Each condition had its own script with identical parameters aside from those defining the condition. Two three up, one down procedure was used in all cases to converge on the 79.4% correct level, (22) that is, for the amount of disparity to decrease by the appropriate step size (the difficulty to go 'up') three successive correct identifications of the target patch had to occur (see figure 2.11 for an example). If at any level of disparity the target patch was incorrectly identified, the amount of disparity would increase by the appropriate step size. The step sizes were predefined for all experiments designed to speed up acquisition of depth detection threshold.

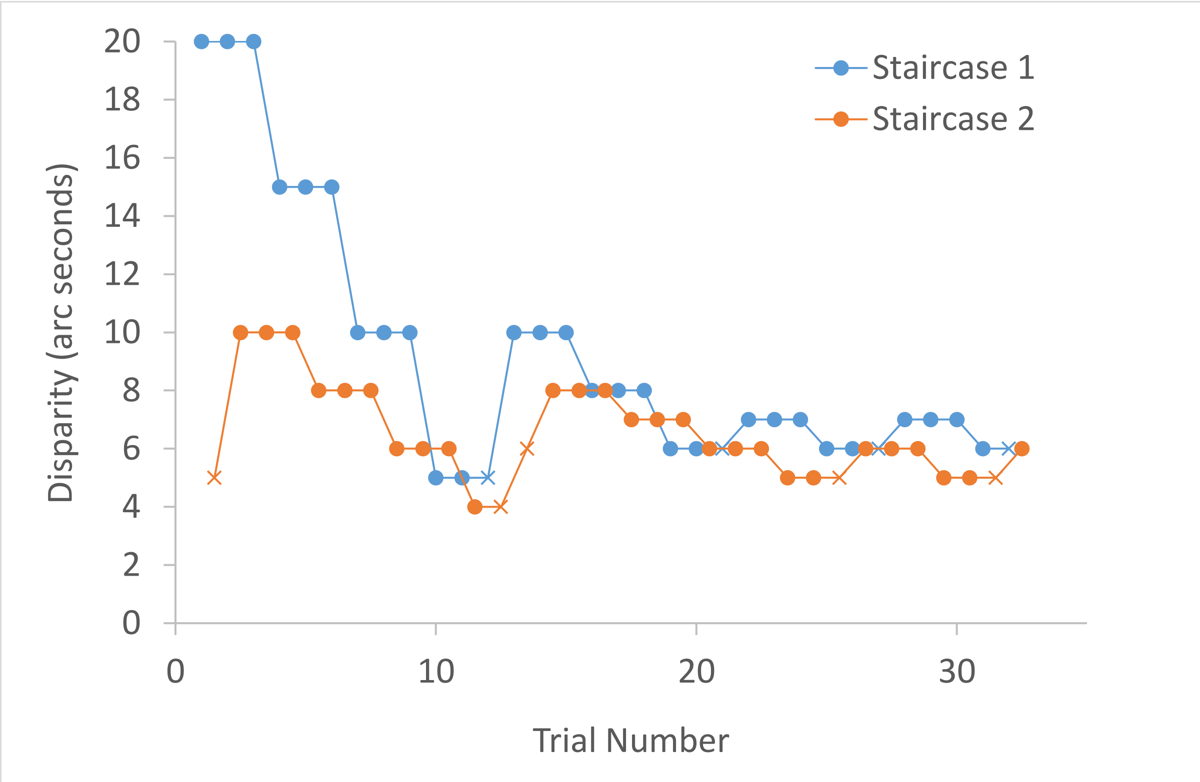


Figure 2.11: Example two staircases converging for one condition using a three up, one down procedure. An incorrect response is represented by a cross, as is shown in the plot. Three correct responses are required for the task to become harder (disparity decrease), however one incorrect answer will make the task easier (disparity increase). This disparity threshold is approximately 6" in this example.

The same three up, one down procedure was used in the following experiments, but a development of the experiment control library, multiStairHandler was used instead. This allowed the conditions to be interleaved, running within one script. More detail is given within each chapter.

Experiment response recording

Every experiment required a response on a four-alternate forced choice basis, with the layout on screen identical between experiments as shown in figure 2:12. A four-alternate forced choice experiment is where four possible options are given to the participant to choose from. For the experiment to continue, the participant must choose one of the four choices: this constitutes the 'forced' part of the procedure. To aid ease of subject response, a button box was made in the same format as the onscreen layout. The button box consisted of the control board from a USB keyboard, with specific combinations of contacts attached to push buttons to report each individual response.

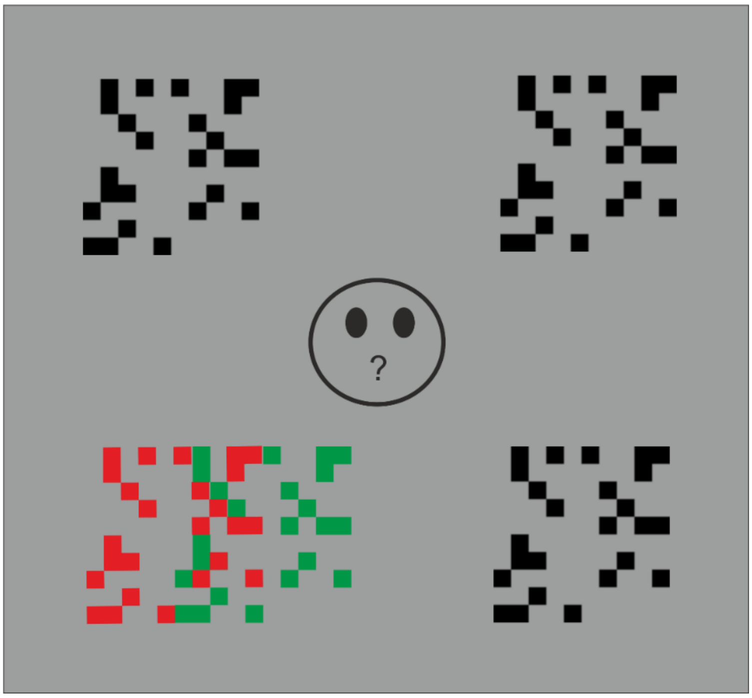


Figure 2.12: Schematic of stimuli on screen. When observed on a 3D monitor while wearing 3D glasses each half image of the bottom left stimulus in this figure would be presented to each eye individually, and appear in front of the screen. The lower left stimulus shows a target stimulus with a disparity between the right (red) and left (green) half images of 0.05° (10 pixels). (Red and green colouring are for illustrative purposes only)

Stimuli display

A four alternate forced choice (4AFC) procedure was used, with the target random dot stimulus (presented with crossed disparity compared to the screen) and three distractor stimuli (presented with zero disparity) surrounding a central fixation target (presented with zero disparity) with a diameter of 0.36° (76 pixels) (see Figure 4.2). Within each condition for all experiments (unless detailed individually in a chapter), the three distractor stimuli differed from the target stimulus only in the difference of lateral positions of the left and right half-images. The fixation target acted as a feedback mechanism: green colouring indicated a correct response with red indicating an incorrect response. Each stimulus subtended 0.5° (100 pixel square), wherein dots of 0.05° (10 pixel square) were randomly distributed with a density of 25%. The stimuli were pre-computed using Matlab (Mathworks®) and presented on a grey background with 98.5% Michelson contrast and a mean luminance of 9.75 cd/m^2. The inner corners of each of the four stimuli were initially separated from the centre of the fixation target horizontally by 0.6° (120 pixels) and vertically by 0.68° (135 pixels). The maximum disparity level was 0.15° (30 pixels) to avoid overlap of the left and right half-images of neighbouring stimuli, thereby precluding cues to motion-in-depth through unmatched stereopsis. (23,24) All stimuli were visible for a total of one second, with the stimuli position and or pattern changed every 6 frames. This allowed the perception of relatively smooth motion while avoiding the perceived contrast reduction that can occur for rapidly changing patterns.

Experiment set up

All experiments were carried out in the dark to reduce the influence of external factors. The LG display was mounted on a moveable trolley with the monitor at a fixed height. The height was fixed so that the centre of the screen was aligned with the eye level indicator on the chin rest. By aligning the participants eye with the eye level indicator, perfect alignment with the centre of the screen was ensured, minimising the likelihood of any crosstalk occurring.

Statistical Analysis

To obtain depth detection thresholds for each participant, a cumulative Weibull function (eq. 1) was fitted to the proportion of correct responses as a function of disparity level. (25) Chance level (B) in a 4-AFC experiment is 25%, and the asymptote (A) value was set to 1. The parameters estimated were the steepness of the curve (d) and the location of the curve (c). We use c as our threshold, as this represents the disparity level at which observers achieved a 72.41% correct response.

$$\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{A} - (\boldsymbol{A} - \boldsymbol{B}) \times \boldsymbol{exp}\left(-\left(\frac{\boldsymbol{x}}{\boldsymbol{c}}\right)^{\boldsymbol{d}}\right) \qquad \text{(eq. 1)}$$

The lower bound of c was set to zero and the upper bound was set to 1086”. As a criterion for exclusion, we used the goodness of fit value of the cumulative Weibull function; if $r^2<0.3$ in all conditions, the subject was excluded from further analysis. For each comparison, thresholds were only used from subjects who provided a reliable response in the conditions included in the planned comparison.

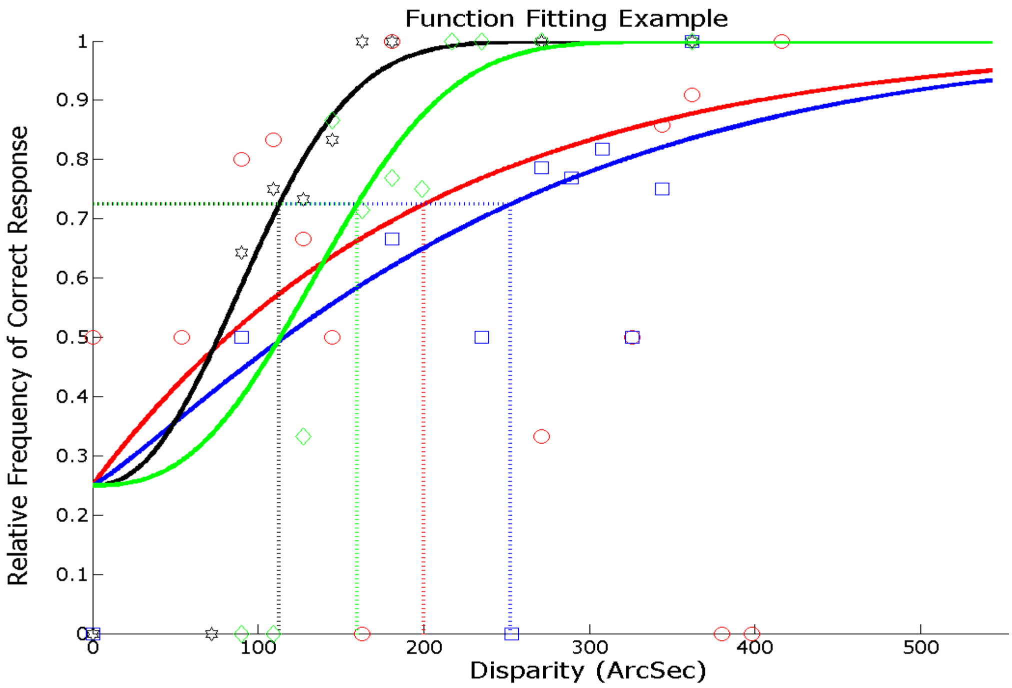


Figure 2.12: An example of the fitting procedure demonstrating two good (upper two lines), and two poor fits (lower two lines). The Diamond and Star points are well fitted by the Weibull function (r^2≈0.8) whereas the Square and Circle points do not follow the function to the same degree (r^2≈0.4).

This procedure finds the best-fitting sigmoidal curve given the data points with weighting considered (i.e. the relative frequencies at each disparity level) using the 'non linear least squares' optimisation method available in the 'fit' function of MatLab; two parameters are fitted for each data set: the location of the curve along the x-axis, and the steepness of the curve. Threshold is defined as the disparity level where the observer achieves 72.41 percent correct. For an example of the function fit to the data see figure 2:12.

As a threshold was always provided by the function, an arbitrary criterion was necessary to avoid erroneous conclusions being formed. To be included in the analysis, it was required that at least one out of the four conditions resulted in a reliable Weibull fit (r^2 of at least 0.3), to demonstrate the subject understood the task.

Details of analysis carried out are included in each chapter.

Chapter Three – Dynamic cues to binocular depth

This experiment tested a total of 32 subjects to pilot the newly developed stereomotion stimuli and to assess the experimental paradigm to determine if the variations in the stimuli provided measurable differences between the stimuli.

Introduction

A proportion of the population have binocular vision deficits, with the prevalence of strabismus between 2.3% and 3.6% in young children alone. (26-29) These deficits often lead to reduced or absent stereoacuity when assessed with current clinical methods. At the same time, qualitative work has shown, that even in the absence of clinically measurable stereopsis, the experience of compelling 3D volumetric depth is reported when viewing dynamic stereoscopic stimuli such as 3D video. (30-32) The discrepancy between clinical measures and patient reports may be due to the limitations of clinical tests, or additional cues present in stereoscopic entertainment media.

Multiple monocular cues to depth are present in video, which provide the perception of depth considered as compelling, as binocular disparity based depth information. (33) Binocular disparity is not the sole cue used to extract depth information, however, it is an important indication of the quality and control of an individuals' binocular single vision. In clinical ophthalmological practice, testing currently only assess once facet of this, namely static binocular disparity. Motion is useful for the detection of depth order, the determination of shape, and the discrimination of movement through depth, motion should therefore be considered as an important binocular cue.

Motion in depth, present in both monocular and binocular stimuli, provides the impression of movement of a stimulus through depth, toward or away from the observer. The presence of this stereomotive facet of stereopsis has been demonstrated in the absence of measurable static stereoacuity. Of 42 subjects who were unable to identify depth on a static stereoacuity test which displayed disparities up to 1200” (Titmus stereo-test), 22 were able to identify binocular motion in depth at a threshold of 500” or smaller. (13,14) Other studies suggest that the presence of changing disparity results in the identification of motion in depth, where static disparity demonstrated no depth. (11,12) Furthermore, the time taken to identify which target is closest to an observer is significantly shorter when the target moves through depth even if the stationary presentation has a larger amount of disparity. (9) When asked to compare static and stereomotion targets, observers matched smaller amounts of disparity where motion in depth is present, to a static disparity target. (8) The presence of motion in depth enhances the perception of depth.

Motion in depth (a Depth Change) contains two binocular cues, changes in disparity over time (CDOT) and interocular velocity differences (IOVD). (6,34) The CDOT mechanism determines the amount of spatial disparity present between the images projected onto each retina, continually monitoring for changes. If the amount of disparity of an object seen in depth increases or decreases over time, the object is perceived to be moving towards (looming) or away (receding) from the observer. The IOVD mechanism does not rely on determining spatial disparity, rather it uses the motion of the images projected onto each retina, and based on any difference between the motion in the left and right eye (speed or direction) perceives motion through depth. It appears also that the CDOT cue is used by most individuals in isolation whereas fewer are able to use the IOVD. (2)

While these studies agree that the presence of motion in depth can demonstrate binocular function in the absence of measurable static stereoacuity, there are a number of limitations of the methodologies employed, such as the comparison of different disparity ranges and using differing presentation methods (computer display vs paper based testing) between the static and stereomotion conditions. Also, the previous studies investigated the perception of motion in depth, rather than depth detection per se.

Therefore, the aim of this chapter is to directly compare static and dynamic conditions, using stimuli presented on the same device, to determine if stereomotion cues to depth result in lower thresholds than static cues.

Methods

Experimental conditions

The main comparison in the experiment was between the static and depth change conditions, but to further investigate stereomotion depth cues, we included a CDOT only condition for comparison. Further, a fourth condition was also introduced as a control for the CDOT condition. The order of presentation of these conditions was randomised for each subject. All stimuli were displayed for a total of one second. The features of each condition are as follows:

1. STATIC: Stimulus is presented at a fixed amount of disparity. Between each trial the pattern of dots changed.
2. Z-LOCATION CHANGE: Each half-image consisted of the same pattern of dots during the one second presentation, however, every 167ms, an increase in the amount of disparity occurred from the initial disparity of 1/6th of the target disparity. E.g. for a target disparity of 60”: in the first 167ms the disparity was 10”, increasing to 20” for the next 167ms, and then up to 60” for the final 167ms of the presentation time. Between each trial the pattern of dots changed.
3. CDOT: This condition is similar to the Z-LOCATION CHANGE condition, however on each change in disparity, the pattern of dots making up each patch also changed in the target and control patches.
4. STATIC CHANGING PATTERN: To ensure any differences between the dynamic and CDOT conditions were not due to the changing pattern of dots

during presentation, this condition is identical to the STATIC condition with the pattern of dots changing every 1/6th of a second. E.g. for a target disparity of 60”: for the first 167ms the disparity was 60” with one pattern, for the next 167ms the disparity remained at 60”, however a different pattern of dots was presented, etc.

To exclude any cue from monocular viewing or from motion alone indicating the correct response in the conditions with changing disparity (Z-LOCATION CHANGE and CDOT), lateral motion was introduced to the three distractor patches in the stimuli. The amount of motion was identical to the distance moved by the target patch, occurring every 167ms, however rather than the half images moving in the opposing directions to create crossed disparity, the non-target patch half images moved in the same direction, thereby providing the same amount of retinal motion, but zero disparity change.

Results

In total 32 subjects aged 18-41 years were recruited, screened and took part in the experiment. The average interocular visual acuity difference was mean (±SD) 0.04(±0.04) LogMAR. Reliability of function fit was analysed for each participant, seven of which were excluded as they did not meet the criteria. The mean (±SD) age of the remaining subjects were 25 (±1.2) years.

The mean(±SD) thresholds derived from the psychometric function fits in each condition were as follows: STATIC 182”(±100”), STATIC CHANGING PATTERN 241”(±128”), Z-LOCATION CHANGE 120”(±60”), CDOT 167”(±109”) (see figure 3.4). The thresholds were analysed using a 2-way ANOVA, with ‘pattern type’ being a factor (changing/static) and ‘disparity type’ the other factor (static/changing). We find two main effects: stereoacuity thresholds are lower when the disparity information changes during presentation ($F(1,80)=9.33$, $p<0.01$), and changing the pattern during presentation leads to an increase in thresholds ($F(1,80)=5.35$, $p<0.05$) (figure 3.1). There is no significant interaction between the two factors ($p=0.81$).

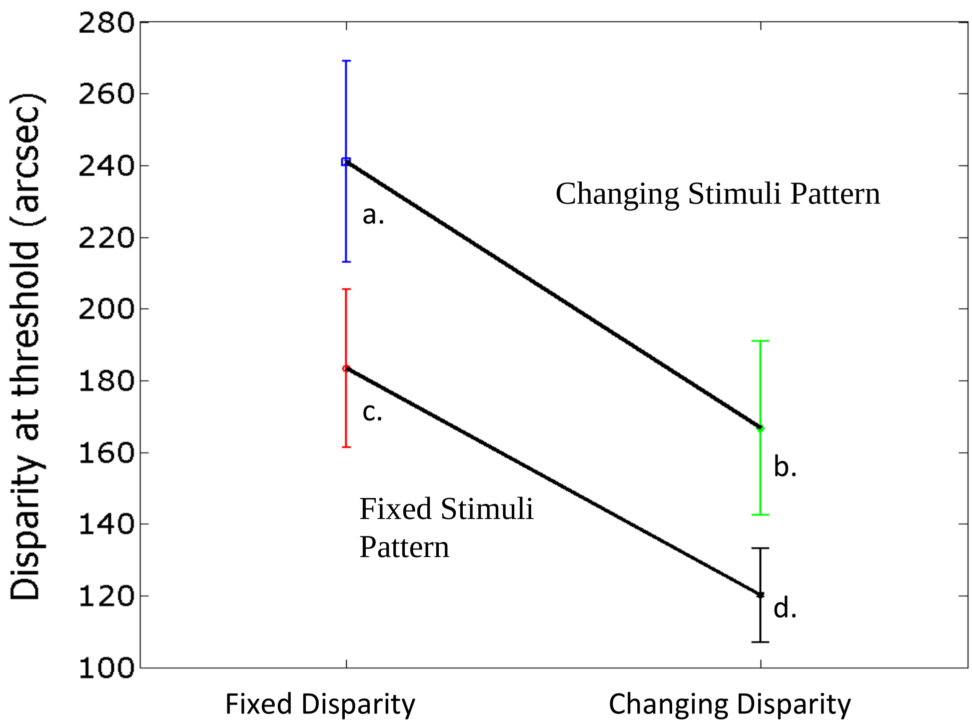


Figure 3.1: Plot of Mean (error bars = ±SD) threshold disparity for each condition. a) STATIC CHANGING PATTERN b) CDOT c) STATIC d) Z-LOCATION CHANGE

Discussion

In previous studies, (31,32) subjects reported compelling depth perception when viewing stereoscopic 3D entertainment media when a large variety of cues to depth were present in the stimuli. The aim of the current experiment was to remove monocular cues to depth to investigate the contribution of dynamic disparity information for depth detection.

By directly comparing thresholds for static and dynamic conditions using stimuli presented on the same device with the same settings (display duration, size, contrast, colour, display method, luminance, testing protocol), we can conclude that it is the stereomotion that confers a benefit on individuals' depth detection. This finding provides a potential explanation for the observation that those without measurable static stereoacuity seem to perceive volumetric 3D depth at the cinema, (30,31) and can accurately report changes in depth when presented with motion. (11-14)

The lowest thresholds were found for the Z-LOCATION CHANGE condition (Changing Disparity/Fixed Pattern), which is consistent with the idea that the CDOT cue alone is not solely responsible for depth detection of motion-in-depth stimuli, but that another cue, the IOVD cue, might be utilised, in line with previous reports. (2)

Additional experiments have been conducted to determine if an isolation of the IOVD cue results in the perception of depth. By definition, no disparity information is available in the IOVD cue, as no spatially corresponding points exist between the two eyes; the IOVD cue signals only a change in position. Indeed, of 132 subjects assessed in a subsequent study, only 12 were able to provide a reliable fit in the IOVD only condition, with thresholds significantly higher than any other condition. (35)

Of the 32 subjects tested, seven were not included in the analysis as they did not provide a reliable function fit in at least one condition. As the population of subjects used in this study were not familiar with psychophysical testing methods, it is not unexpected that a considerable proportion did not provide reliable data. A study using similar stimuli to display similar cues found that only half of their 62 subjects provided thresholds for use in analysis. (2) The level of stereoacuity (e.g. STATIC 185”) measured in the study sample may appear poor; this is due to the design of the stimuli used in the experiment. The aim was not to measure absolute thresholds, but to allow comparison between the different conditions without creating a ceiling effect due to the relatively large pixel size in the display.

By introducing lateral motion to the distractor patches in the stimuli in the CDOT and Z-LOCATION CHANGE conditions, we aimed to ensure the subjects were not responding on the basis of monocular retinal motion alone. (6) Whilst no lateral motion was programmed in the target stimulus, a degree of lateral motion can be perceived in stimuli moving through depth, as the lateral motion is more readily detected than the depth change. (36)

The data presented here provides evidence that the human visual system can utilise stereomotion information more effectively than static disparity signals, corroborating work performed by Weldon *et al.*. (9) This is distinct from other studies mentioned here, where the ability to detect motion was assessed. Our finding that stereomotion disparity processing is superior to static processing warrants further investigation and potential development of a clinical test, to allow the full assessment of binocular potential to assist management decisions. Binocularity may be demonstrable when tested with a binocular test including stereomotion, where absence of response is found during static assessment.

Chapter Four – A systematic comparison of static and dynamic cues for depth perception

This chapter builds on the previous chapter by introducing two further stimuli to determine the contribution of other potential cues which may be beneficial to depth perception. The format of the experiment also changes from a blocked design to an interleaved design to reduce any learning effect that may occur during blocked presentation. While standard clinical stereovision tests involve stationary stimuli with a given static disparity, dynamic 3D stimuli can involve movement across the screen (x or y location change), variations of the surface pattern of stimuli over time (pattern change), and/or changes in the amount of simulated depth over time (z location change, or "stereomotion"), each of which could affect the observer's ability to extract stereoscopic information. This chapter will evaluate the effectiveness of these stimulus characteristics with the addition of stimuli that move across the screen.

Introduction

When the two retinal half-images of an object fall on corresponding points in each eye (e.g. a fixation target in the central fovea), it has zero disparity (see "A" in Figure 4.1), and where non-corresponding retinal locations are stimulated, a disparity is present. For a stimulus whose half-images are displaced in a temporal direction with respect to each other, the disparity is crossed, and the relevant stimulus feature appears to be nearer than the zero disparity object (see "B" in

Figure 4.1). If such an object were to move laterally across the screen, both of its retinal images would translate at the same velocity (i.e. at the same speed and same direction), such that the disparity does not change over time, and the object appears to translate without a change of depth (see "C" in Figure 4.1). However, for objects moving through depth towards an observer the amount of disparity relative to the fixation point changes over time, resulting in retinal motion in opposite directions and/or at different speeds in each eye (see "D" in Figure 4.1).

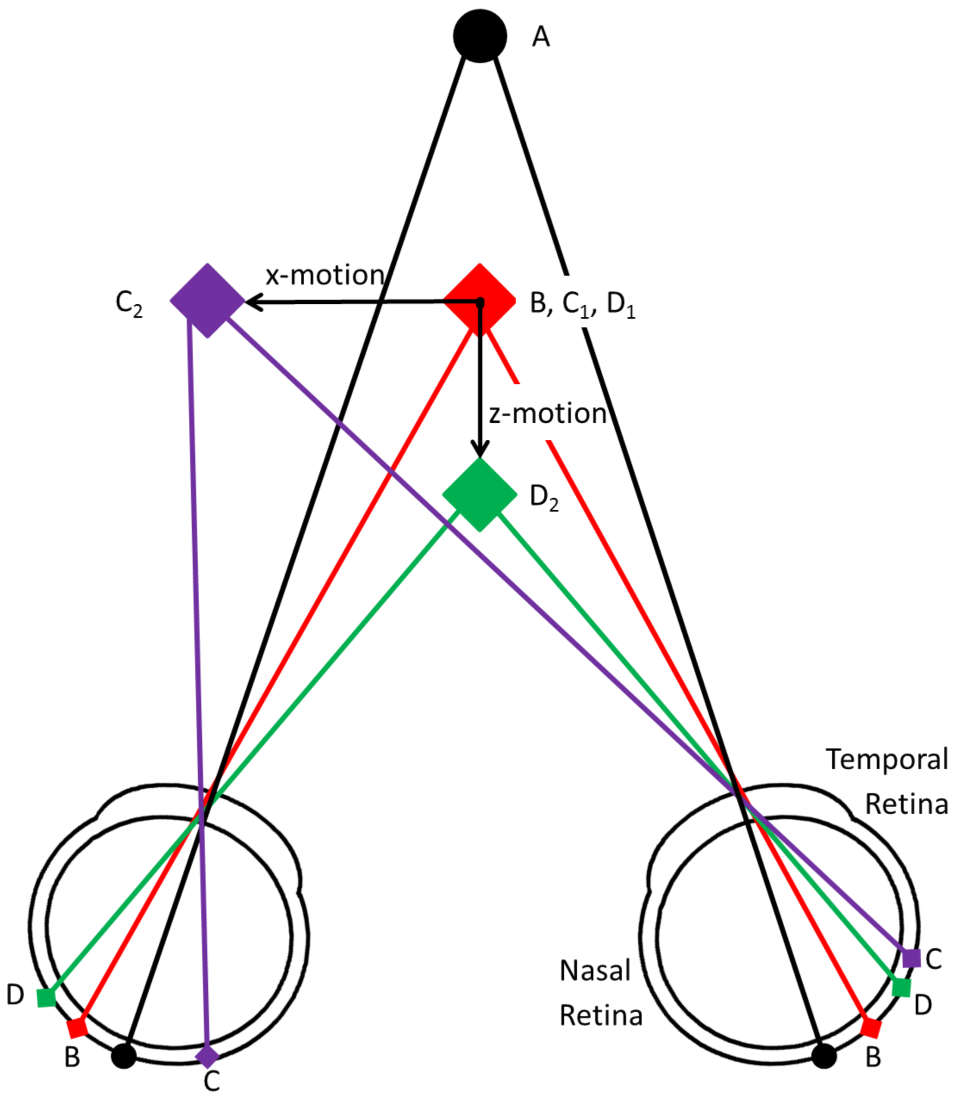


Figure 4.1. Plan view of various stimuli and their binocular retinal projections. A) The fixation target (stationary, zero disparity). B) A stationary stereoscopic stimulus

with a crossed disparity. C) A stimulus moving laterally (x-motion) at a constant disparity. D) A stimulus moving in depth (z-motion), changing its disparity as its half-images translate at different velocities across the retinae. In all cases subscript 1 denotes the start location at time 1 (B on retina) and subscript 2 is the next location at time 2 (C and D on retina)).

Disparity change in particular has been considered the most likely candidate for residual stereopsis in those clinically defined as stereoblind (no measurable stereoacuity on standard clinical tests); quantitative work has shown that stereoblind subjects are able to correctly identify the approaching or receding motion of stimuli when changes in depth are simulated stereoscopically in laboratory stimuli. (11-14,16,37) However, in these studies observers were asked to judge motion and not depth. In studies measuring subjects' ability to appreciate depth in stereoscopic stimuli, it appears that non-stereoblind observers perceive a greater amount of depth for stimuli involving approaching or receding motion, compared to static stimuli. When asked to match the amplitude of depth of a static disparity target to one with changing disparity, participants always set a smaller amplitude of disparity for the moving target. (8) Moreover, when observers were asked to detect depth in an approaching target that begins with zero disparity, this can be achieved more quickly than for a stationary target with a larger disparity, indicating an enhanced sensitivity for dynamic stereoscopic targets. (9) Zinn & Solomon (1985) measured the time taken for participants to determine the closest of four binocular targets with various relative disparities, as they moved through depth towards the participant. (10) The amount of time taken to determine the closest target did not correlate significantly with static stereoacuity scores as measured with either the TNO or Titmus tests. Although this null result appears to suggest that levels of performance with moving and stationary targets are unrelated, the differences between stimuli and procedure for the two tasks make a direct comparison difficult since other stimulus- and task-related parameters may affect the performance.

The presence of a changing pattern in dynamic stimuli may result in an improved detection of depth, due to the presence of several independent samples and thereby increasing the reliability of estimating depth and solving the correspondence problem. (38,39) We aim to further investigate the effect of a pattern change on depth detection thresholds.

Another element of a dynamic display is lateral motion in addition to disparity. Thresholds for detecting depth are not affected when the lateral velocity is below 2^{o} per second, but worsen exponentially as the velocity increases from 2^{o} to 12^{o} per second. Control experiments found that this effect was not primarily due to exposure duration or increasing target eccentricity, but the reduced performance is due to fast lateral motion. (40)

It is important to note also that comparisons of stereoscopic performance between dynamic and static stimuli have been made using fundamentally different test types, for example computerised/projected disparity change stimuli compared to book based tests. (12-14) As a direct comparison between clinically used book-based static stereoacuity tests is not possible as each provides a different threshold for the same individual, (41,42) the differing findings of static and dynamic tests may be due to variations in test design rather than the presence or absence of static and dynamic stereopsis.

This chapter investigates the influence of various characteristics of dynamic stereoscopic stimuli on the detection of depth in direct comparison to static stimuli. We include stimuli that either feature or lack changes of disparity, of horizontal location, or of stimulus pattern. By assessing these stimulus characteristics under equivalent conditions direct comparisons between dynamic and static depth detection thresholds are possible.

Materials and Methods

To determine the contribution of each aspect of dynamic stereoscopic stimuli to the detection of depth, six specific stimulus conditions were included. In each case, the appearance of the four stimulus patches on each trial was designed to be similar, aside from the target stimulus being defined by a separation of the right and left half-images.

1. **STATIC**. Target stimuli were presented with a fixed disparity. Both the stimulus' frontoparallel location and its dot pattern were constant throughout.
2. **PATTERN CHANGE**. The left and right eye images were presented with a fixed disparity and location. The dot pattern changed to a novel random array of dots every screen update.
3. **X-LOCATION CHANGE**. Stimuli were presented with a fixed disparity and lateral motion with a total displacement equivalent to half of the target stimulus' disparity. Importantly, each half image moved in the same

direction (no disparity change), simulating lateral motion. The dot pattern was fixed.

4. **Z-LOCATION CHANGE**. Target stimuli were presented with a disparity that changed over time (starting at zero and increasing towards the target disparity), but with a constant location and dot pattern. Many observers perceive these stimuli to move laterally as they approach, a percept that is more likely in observers for whom there is substantial suppression of one eye's input. (6) To ensure that this artefactual percept could not be used to provide the correct answer in our 4AFC task, randomised rightward or leftward motion was added to the three distractor stimuli. The two half-images of each individual distractor stimulus moved simultaneously in the same direction and by the same distance as the target stimulus' half images.
5. **Z-LOCATION & PATTERN CHANGE.** Target stimuli were presented with a changing disparity (as for the Z-LOCATION CHANGE stimulus), while the dot pattern also changed to a new random array every screen update. As for the Z-LOCATION CHANGE condition, randomised rightward or leftward motion was added to the three distractor stimuli.

In principle, the Z-LOCATION CHANGE condition contains the same information on positional depth as the Z-LOCATION & PATTERN CHANGE condition. However, it also contains a motion in depth cue (Inter-ocular Velocity Difference - IOVD) which provides information on the rate and trajectory of motion in depth. (1-3,6,7) To assess the possibility that subjects might be tempted to select the stimulus that appeared to move in depth, rather than use positional depth signals per se, we included a control condition featuring this cue to motion in depth only. We hypothesised that it would not provide any information on static depth, and hence thresholds would not be recordable.

6. **CONTROL.** Target stimuli were identical to those in the Z-LOCATION CHANGE condition, in terms of the temporal motion of each retinal half-image, the constancy of stimulus pattern and the lack of overall lateral motion. However, in this condition, left and right half-images consisted of different patterns with no binocular correlation. While this eliminates any coherent binocular disparity signal from the target and distractor patches, it cannot be said that there are no disparity signals present at all. The stimulus itself contains many vertical edges in each eye, and although any arbitrary left-right pair of edges could in principle be said to have a disparity, these would be random and inconsistent, forming a cloud of noisy depth signals centring on zero. Although these signals could not be used to complete the task, it is possible that the IOVD cue might be used to identify which stimulus is moving in depth. To prevent the target patch from being detected by lateral motion due to suppression or diplopia, the distractor stimuli featured nasal motion in each half-image.

	Fixed Disparity	Changing Disparity	Fixed Pattern	Changing Pattern	Fixed Lateral Position	Changing Lateral Position	Binocular Correlation	No Binocular Correlation
1. STATIC	✓		✓		✓		✓	
2. PATTERN CHANGE	✓			✓	✓		✓	
3. X-LOCATION CHANGE	✓		✓			✓	✓	
4. Z-LOCATION CHANGE		✓	✓		✓		✓	
5. Z-LOCATION & PATTERN CHANGE		✓		✓	✓		✓	
6. CONTROL	*		✓		✓			✓

Table 4.1 Characteristics of each condition tested. *Note that for the CONTROL condition, the lack of binocular correlation means that there is no coherent disparity. However, it is possible that local features may be binocularly matched to produce a noisy "cloud" of disparity signals centring on zero. The dots of the stimuli on the left and right retinae move in the same way as they would in the Z-LOCATION CHANGE and Z-LOCATION & PATTERN CHANGE conditions to reach their target relative displacement (see description of condition 4).

Procedure

In each session, all six condition staircases were randomly interleaved. Two thresholds were estimated for each condition by separate staircases (Multistair handler functional of Psychopy (21)), one starting at a large disparity (362”), and the other at a small disparity (90”) to ensure the starting value did not systematically affect the final threshold. The initial step size was 95”, which after three reversals was reduced to 38”. After a further two reversals the step size was halved to the minimum step size of 19’’. A three-down-one-up method was used so that the staircases converged to a performance of 79.4% correct. (22) The staircase for each condition terminated when eight reversals occurred or if 150 trials were reached. Note that for the CONTROL condition the variable controlled by the staircase was maximal horizontal retinal displacement, which is applicable to stimuli lacking binocular correlation while being equivalent to retinal disparity in the other conditions.

Statistical Analysis

To determine whether dynamic stimuli result in lower depth detection thresholds than static stimuli, planned comparisons were made between the STATIC vs. PATTERN CHANGE; the STATIC vs. X-LOCATION CHANGE; the STATIC vs. Z-LOCATION CHANGE, and the STATIC vs. Z-LOCATION & PATTERN CHANGE conditions. To examine the potential use of artefactual motion-in-depth signals in our depth detection task (i.e. participants choosing the stimulus that appears to move in depth, rather than the stimulus that appeared closer), a comparison was made between the STATIC and the CONTROL condition, which appeared to move in depth despite having an undefined disparity. As a total of six individual paired comparisons were made using paired t-tests, Bonferroni corrections were applied to maintain a family-wise α of 0.05. The corrected α value was $\frac{0.05}{5}$ = 0.01. In addition, a supplementary 2x2 ANOVA was performed to examine the factorial combination of the two independent variables of pattern (fixed/changing) and depth (fixed/changing).

Results

In total, 127 subjects (85 Female, 42 male; mean (SD) age 21 (5) years) who passed screening were assessed. Of these, 19 were excluded on the basis of unreliable performance (see threshold estimation in methods). Table 4.2 provides an indication of the conditions where subjects were most and least able to detect depth by the remaining 108 subjects, with Figure 4.2 showing threshold performance for each of the conditions.

Table 4.2: Number of subjects in each condition who provided a satisfactory Weibull fit, and whose thresholds were subject to further analysis (n=108).

	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
% Satisfactory Fit (n)	61% (66)	61% (66)	53% (57)	59% (64)	66% (71)	11% (12)

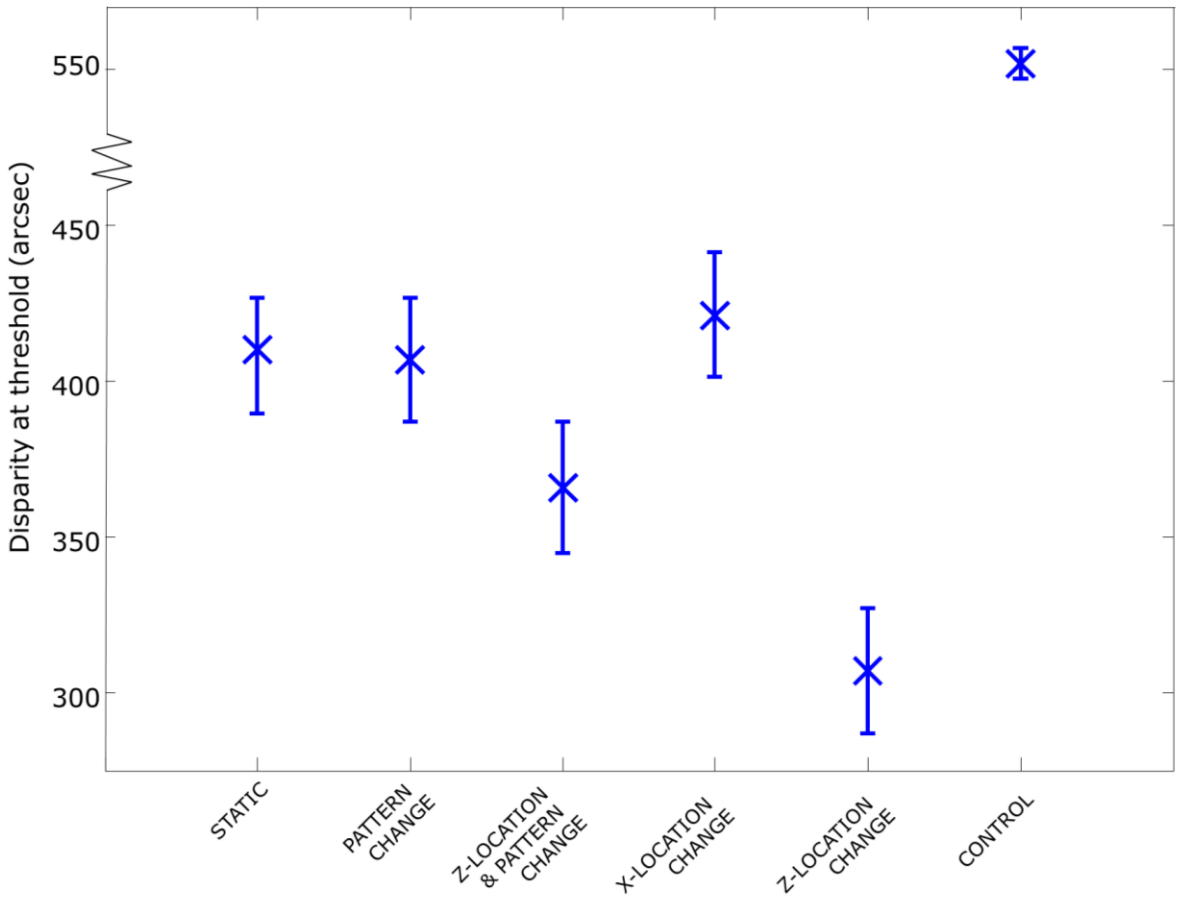


Figure 4.2: Mean (±1SEM) depth detection threshold for subjects who met the defined criteria. The number of subjects for each condition is as stated in table 4.2.

Do dynamic stimuli results in lower depth detection thresholds than static stimuli?

Neither the comparison between the STATIC and PATTERN CHANGE ($t(43)=0.37$, $p=0.71$) conditions, nor the comparison between STATIC vs. X-LOCATION CHANGE ($t(47)=-0.84$, $p=0.405$) conditions showed a significant difference. However, a different pattern emerged for stimuli that featured motion in depth. A comparison between STATIC vs. Z-LOCATION CHANGE conditions showed a significant difference between thresholds ($t(46)=6.55$, $p<0.001$), while the Z-LOCATION & PATTERN CHANGE stimulus also yields a significantly lower threshold than the STATIC condition ($t(42)=5.40$, $p<0.001$). This indicates that the presence of changing disparity enhances the detection of depth, while there is no evidence of any such enhancement for changing stimulus patterns or for stimuli moving laterally.

Factorial combination of pattern and z-location change

The factors of Z-LOCATION CHANGE and pattern change were subjected to additional scrutiny in a 2x2 within subjects ANOVA to assess their effects and the possibility of interactions. Of the 108 subjects, 27 were able to provide a reliable threshold in each condition included in this analysis. Data are represented in Figure 4.3. Here, thresholds were lower for conditions involving changing depth: an observation that was confirmed by the presence of a statistically significant main effect of Depth ($F(1,104)=8.23$, $p=0.005$). No main effect of Pattern was found, as indicated by the similar thresholds for the two plots ($p=0.947$). The interaction between Pattern and Depth was not significant ($p=0.757$), indicating that the enhancements brought by changing depth apply equally to all stimuli regardless of the persistence of the pattern.

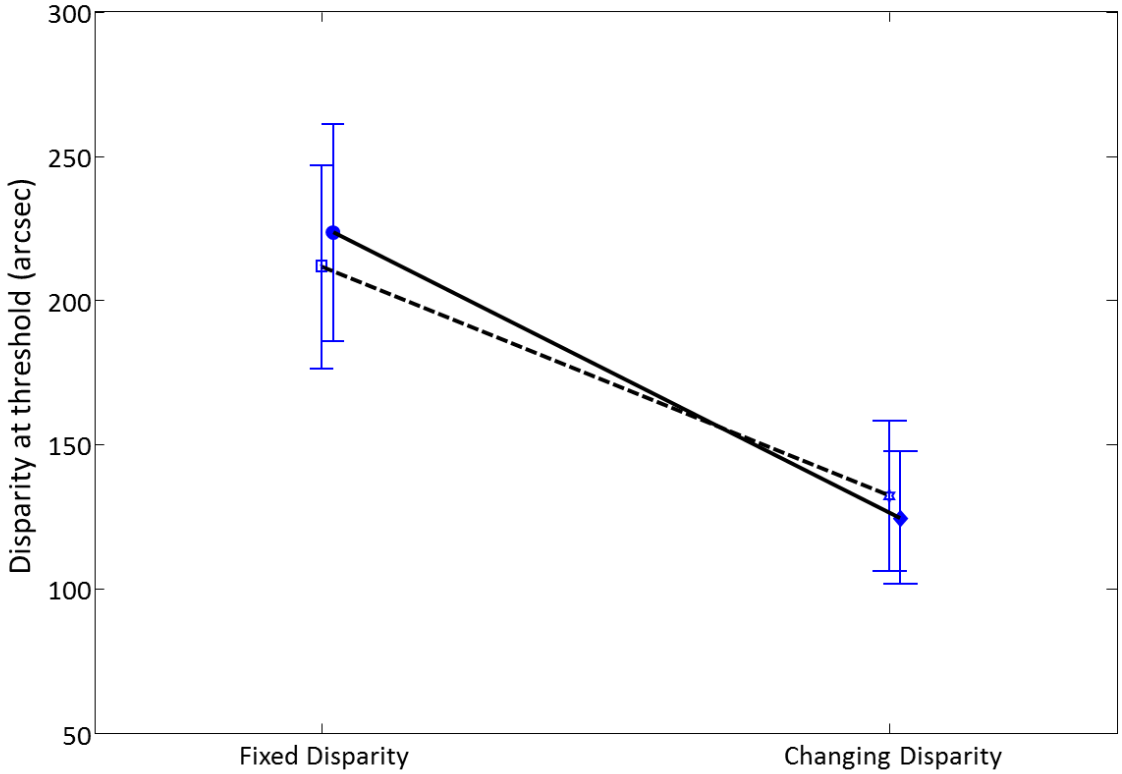


Figure 4.3. Factorial combination of the Disparity and Pattern factors. Error bars represent ±1SEM, the dotted line signifies the changing pattern conditions. (n=27)

Control for the use of non-disparity signals

To assess the potential for motion in depth signals (in the absence of disparity signals) to contaminate the measurement of depth detection thresholds, we used a CONTROL condition that includes the IOVD cue to motion in depth. The median threshold for this condition was at ceiling level, with only 11% of subjects able to use this cue reliably (see table 4.2). This confirms the hypothesised inability of the vast majority of subjects to glean any positional depth information from this cue. For the small number of subjects who did record thresholds in the CONTROL and

STATIC condition, they were significantly higher than for the STATIC condition (t(7)=-3.67, p=0.008).

To ensure that no monocular cues were used to identify the target stimuli, a small group of subjects (n=3) participated in an additional control experiment, where all conditions were viewed as described above with additional occlusion of one eye. Under these monocular conditions, no subject was able to perform the task in any condition, demonstrating that there were no informative monocular depth cues present.

Discussion

Dynamic stereoscopic stimuli and the perception of depth

The experience of depth perception during stereoscopic film/TV viewing has been reported in observers lacking clinically measurable stereoacuity. (31) In the aforementioned study, no attempt was made to identify the factors that may contribute to the perception of depth in dynamic displays. The aim of the current study was to isolate the characteristics of dynamic stereoscopic stimuli and to establish their contribution to depth detection. While there have been reports of dynamic stimuli resulting in better stereoscopic performance, (11-14) (in terms of preserved ability to detect stereoscopic motion in depth, despite the absence of static stereopsis), to the best of our knowledge our study is the first direct comparison of depth detection between static and dynamic stimuli. We have shown that for some dynamic stimuli, lower thresholds are common for many observers. This advantage for dynamic disparity information is specific to motion in depth and does not occur for patterns moving horizontally, or for those that change their surface pattern over time (temporally decorrelated).

Task Difficulty

Of the 127 subjects, we excluded 19 from the analysis as these subjects failed to provide reliable responses in any condition. We were interested in testing depth detection performance in a representative sample of a normal population, where a number of participants are unable to perform psychophysical experiments, (2) whereas these types of studies are often performed on a small set of highly experienced observers. (43) All subjects demonstrated the presence of stereoscopic vision during screening (stereo fly test circles <200”) but only 61% of subjects were able to provide a reliable response in the STATIC condition. The reason for this could again highlight the non-comparability of stereotests but there are a number of other reasons for this.

It could be suggested that subjects did not understand the task, did not comply with instructions given or were unable to detect any depth within the one second presentation. As shown in table 4.2, no condition yielded satisfactory fits for all subjects, with 53-66% meeting our criterion in the first five conditions, suggesting similar task difficulty across these conditions. The variability in the percentage of reliable fits follow a similar pattern to the thresholds, e.g. the most reliable condition was the one in which depth detection thresholds were lowest.

To further ensure the exclusion were not an artefact of the Weibull fitting procedure, we verified that using the last four reversals of each condition as the threshold for each of the 127 subjects tested (converging at 79.4%), yielded thresholds similar to fitting the Weibull (threshold is defined as the disparity corresponding to 72.4% correct). The discrepancy between these two methods was always less than 6.5%, and the pattern of the results is not affected by the method used to derive the threshold.

Further, to ensure our arbitrary cut off criteria of r^2=0.3 did not represent heavy filtering which may bias our results, we repeated the analysis. This demonstrated that the analysis is robust and does not depend on the exact value of r^2 used as a cut off; the conclusions do not change when an r^2 of 0 is used.

The average level of stereoacuity in the population tested may seem poor (ranging from 180” to 351” across conditions), compared to previously published thresholds of less than 5”. (44) A recent large scale study of 1060 participants however, shows that the median, stereoacuity score on the TNO stereo tests are 60”, and 88” in a adaptive staircase test with a similar eccentricity in stimuli as used in this thesis. (45) However, our intention was to test a large sample of observers with differing levels of stereoscopic proficiency. In addition, our experiment was not designed to measure the limits of stereoacuity under optimal conditions, (42) but rather to examine the relative effectiveness of dynamic vs. static cues to depth. Even so, ten subjects were able to perform with high precision at one pixel disparity (18.1”), the minimum disparity presented. This level of acuity falls within the range of 12” to 37” in other population studies of stereoacuity in adults considered as normal. (46-48) Other potential reasons for the increased thresholds, may be in part due to the depth cue conflicts present in the stimuli, due to the removal of other cues to depth, such as changing size. As is common in studies of stereo/stereomotion, monocular cues to depth are removed with the aim of isolating the cue of interest for investigation. Other factors such as a limited display time, eccentricity of target and spatial parameters may also contribute to the large thresholds measured in this study.

Disparity thresholds depend on spatial frequency with peak stereoacuity (3-4") found at 0.3 cycles per degree when sinusoids are used. (49) Our stimuli are more broadband (in frequency space) and shifted to higher spatial frequencies, well beyond the optimal spatial frequency for stereoacuity. Further it has been demonstrated that stereoscopic discrimination thresholds increase as eccentricity increases, (50,51) with low threshold demonstrated when the subject can fixate directly on the target and comparator with no time constraint. (52)

Facilitation specific to disparity change

To test whether the detection of depth in moving stimuli was specific to motion in depth rather than to moving stimuli in general, a condition using lateral motion with fixed disparity was included (X-LOCATION CHANGE). We found that unlike changing depth, adding lateral motion to a fixed disparity stimulus does not improve stereoacuity compared to a static stimulus with fixed disparity. These findings are in line with previous studies, as the velocities used here are below 2^{o}, a level above which depth detection thresholds worsen. (40) In addition, the effect of changing dot patterns was assessed in a 2x2 ANOVA, which showed neither an effect of changing pattern nor an interaction between changing depth and changing pattern. As such, the effect of changing depth is able to account for all examples of enhanced depth detection compared to the STATIC condition.

A potential confound relating to the z-location change conditions (Z-LOCATION CHANGE, Z-LOCATION CHANGE & PATTERN CHANGE) is that the target stimulus did not contain lateral motion, whereas the distractor stimuli did, to prevent their identification through monocular viewing. The lack of objective lateral motion in the target stimuli could, in principle, reveal the correct answer. However, it has been documented that observers often perceive such stimuli to have a degree of lateral motion (due to a bias in the perceived speed of one of the half images), just as the distractors do, hence preventing subjects from using this cue. Even if this had not been the case, we believe that the use of this cue is unlikely, as not only would these two conditions have to be identified out of the six interleaved, but any lateral motion perceived in the motion in depth stimuli would need to be ignored, the change in binocular disparity ignored, and solely the difference in lateral motion be identified.

Methods to avoid this potential confound would introduce further confounds; by adding lateral motion to the distractors and target, there would still be a greater amount of lateral motion in the target stimuli. If a random amount of lateral motion were added to the distractors and target patch a random trajectory for the patch moving in depth would be introduced, and hence a lack of standardisation of this stimulus condition. A random amount of lateral motion added to the distractors, but a constant amount added to the target would result in the speed of lateral translation of the target patch differing from the controls, again providing a method of identifying the target by artifactual means. Additionally, and perhaps most importantly, adding any lateral motion to the target would prevent the research question from being answered; it would produce an oblique trajectory with both x and z motion, preventing the isolation of z-location change.

A further modification could be the use of a random dot background. This was considered during the development of the experiment, but it was difficult to maintain a consistent relationship between the various stimuli features and the background. For example, the introduction and appearance of monocular zones would vary more in the target stimuli, as the half images move in opposing directions.

The possible influence of IOVD on depth detection in the absence of binocular disparity signals was assessed using the CONTROL condition. In this condition, the relative motion of the target compared to distractors is effectively doubled, given that motion of the distractors was equal and opposite to the motion of the target patch. The IOVD cue is most effective in simulating motion in depth when contrasting, or relative motion is present. (53) Alongside controlling for monocular and diplopic cues, the use of doubled stimuli provides the opportunity for good performance in this condition, if the recognition of motion in depth were reported by the subjects rather than depth. Although targets in this condition may have appeared to move in depth, few subjects could give reliable responses, and for the latter, thresholds were high. Of the 11% of subjects who provided a reliable 'depth discrimination' threshold, only three were able to provide a threshold below ceiling

(543”), with a threshold of 161”, 477” and 512”. It is possible that these three subjects interpreted motion towards themselves as being ‘closer in depth’ than the distractor stimuli, as they were asked to identify the patch that appeared closest to them in space. As soon as the target approached it would have appeared closer than the distractors, and as a binocular response was required to correctly identify this, this was defined as a correct response. Feedback was provided in the same manner as in other conditions; we interpreted the identification of the approaching patch as the closest patch as a correct answer and provided positive feedback. While one subject recorded a threshold of 161” (191” in Z-LOCATION CHANGE & PATTERN CHANGE and 182” in Z-LOCATION CHANGE), the other two subjects provided their highest threshold in the CONTROL condition. This lends confidence in our results, confirming that the IOVD cue did not contaminate the conditions in which depth appeared to change over time.

When considering the literature on the ability to detect a change in direction of motion through depth, rather than the detection of depth in moving stimuli, several studies have shown examples of stereomotion blindness with intact static depth perception. This has been demonstrated to coincide in specific areas of a single subject's visual field, though normal performance may be possible in other areas. This 'area' can be either a location in a fronto-parallel plane or a range of disparities. (4,17-19) Cases of intact stereomotion perception in areas where subjects are unable to detect differences in static depth have also been presented in the peripheral visual field of strabismic subjects. (11,16) This evidence is complementary to present findings showing sensitivity to dynamic stereo in the absence of static stereopsis.

Conclusion

We have shown the importance of dynamic stimulus characteristics – particularly of changing disparity – in binocular depth perception. Based on our sample (n=108) of subjects with measurable stereovision, we conclude that this stimulus attribute is a likely candidate to explain some of the discrepancy between some observers' ability to enjoy enhanced depth simulation in 3D movies despite their diagnosis of "stereoblindness". Although it has previously been shown that some stereo-deficient subjects can <u>detect motion</u> in depth from stimuli that approach or recede (11-16,18,37), this is the first study to show that performance for <u>detecting depth</u> through the CDOT cue, is improved under such circumstances, while other dynamic Characteristics such as horizontal motion and varying stimulus pattern have no measureable effect.

Our findings have implications for neurobiological models of binocular vision by providing useful constraints on the relative importance of static vs dynamic disparity signals for depth perception. They suggest that the detection of binocular disparity in z-motion is superior to serial detection of changing static disparities. Dynamic disparity changes (condition 4: Z-LOCATION CHANGE) are ecologically valid signals that arise either from self-motion or from object motion towards the observer; our data show that these dynamic disparity signals are associated with the highest performance for depth detection, consistent with their ecological validity.

Given the omission of changes of disparity, currently used static stereoacuity tests may underestimate the degree of binocular function. With this in mind, the present study constitutes an important first step toward the development of a clinically useful test of dynamic stereoacuity, to reflect real world interactions with depth. (54-58)

Chapter Five - The effect of induced fusional demand on static and dynamic stereoacuity thresholds

Introduction

High grade stereo acuity requires the precise alignment of the visual axis, and the sensory ability to determine the presence of binocular disparity between the left and right visual fields, and use this information to extract depth information. The binocular neurones that detect depth are sensitive to retinal information, regardless of how it is presented: (59) “if fusion is achieved, stereopsis is typically apparent”. (60)

In subjects with good binocular control, the motor fusion system responds to any diplopia perceived, ensuring the visual axis are positioned on the point of fixation, resulting in zero retinal disparity at fixation. However, many individuals experience difficulty with ocular motor control, with varying impact on levels of stereoacuity, for example, the deterioration of fusional control in intermittent exotropia, can lead to in an increase in threshold. (61-64) While the consequences of a breakdown in ocular motor control are seen clinically with patients reporting a variety of symptoms resulting from the effort of maintaining binocular vision, the impact of exerting motor fusion on stereoacuity is not clear, and experiments designed to determine the importance of motor control have resulted in conflicting conclusions.

Studies have investigated the effect of fusional stress on stereopsis by simulating exodeviations of up to 40 prism dioptres (PD) and assessing stereoacuity using the Frisby Davis Distance test (FD2) and the Distance Randot® (DR) test with or without hysteresis. (65,66) Whilst some subjects demonstrated no reduction in stereoacuity as long as no diplopia was present, findings were variable. In other subjects, fusional stress reduced the level of stereoacuity to the next banding of stereoacuity. The choice of stereoacuity test may have contributed to the variability in response, as any change may be encompassed by test/re-test variability. For a 'real' change in stereoacuity to be detected using the DR and FD2 tests, at least a doubling of threshold must be measured. (67-69) This suggests that current clinical tests may not be sensitive enough to detect a change introduced by fusional stress.

In the afore mentioned studies, (65,66) the resolution of this detail has been lost by banding moderate stereoacuity the range of 80-200", and only using the 60", 100" and 200" levels of the DR. This is because clinical stereotests are designed to quantify the degree of impairment rather than measure the abilities of a healthy subject. Using fixed points of fusional stress also introduces variability across subjects as motor fusion varies considerably across subjects meaning that the task would be easy for some, but hard for others. The hysteresis effect allows the achievement of higher levels of motor fusion, which could be easily achieved by others without employing this.

It has been suggested that reduced stereoacuity under forced vergence may be due in part, to the necessity of fine motor movements to perceive fine stereopsis being compromised by fusional demand. (61) If this were the case, it could follow that the effect would be exacerbated if the stereoscopic targets were moving through depth, if vergence tracking were indeed used. It was demonstrated earlier in this thesis that smaller amounts of binocular depth are detected in conditions where stereoscopic targets move through depth, (35) which both suggests that the changing retinal location of the stimulus does not adversely impact acuity, and if stereopsis is perturbed by fusional demand, that vergence is not used to detect depth in stereomotion stimuli.

A difficulty with previous testing has been the use of prisms to induce fusional stress. Aside from the difficulty of positioning and steadily maintaining the position of the prism, an amount of optical degradation would occur, uneven between the eyes unless the prism were split. This could contribute to any effect found. The synoptophore lends itself to maintaining a steady amount of fusional stress, with optically clear and equal optical paths, however the levels of stereoacuity testable on the device are limited in standard configuration. Modified versions are available however that contain computer controlled displays allowing accurate assessment of stereoacuity threshold.

This study therefore aims to evaluate the effect of the fusional stress on stereoacuity in both static and dynamic presentations controlled with a computerised staircase procedure with the ability to present numerous levels of disparity, in subjects undergoing similar stress on fusional control.

Materials and Methods

Subjects

In addition to the main inclusion and exclusion criteria of the thesis, ff the subject had no demonstrable simultaneous perception (demonstrated by the test in figure 5.1.1) they were excluded from testing. Subjects were excluded if they had no demonstrable BV, as fusion would be immeasurable.

Apparatus

Stimuli were presented on a modified clinical dichoptic device: the synoptophore (Haag-Streit, Clement Clarke Ophthalmic) as shown in figure 5.1. The fixation target used in the synoptophore is typically a glass slide retro-illuminated by an incandescent bulb. In our modified device, the lamp holder/unit on each tube was replaced with two identical 1200 by 800 pixel FreeWorld 56D120175 Camera Field Monitor LCD screens run at 60Hz. The eyepiece lens was reduced in strength from +5.50DS to +4.00DS, to account for the increased viewing distance. This adjustment ensured that light entering the eye was collimated, and as such maintained a zero accommodative demand. The experiment was controlled by a Pentium i3, Windows PC with an NVidia Quadro FX4600 graphics processor, running Psychopy. (21) The subject's head rested on the forehead/chin rest integral with the synoptophore, with the eyes aligned with the centre of the screen and fixation target. The screen was positioned 0.25m from the subject; with a horizontal resolution of 1280 pixels distributed over 0.12m with each pixel subtending 0.021^{o} (76"). In order to increase precision, interpolation was used to create disparity steps of 0.084^{o} (19") to be assessed, created though a shift in the luminance of the pixels at the extremes of the stimuli elements.

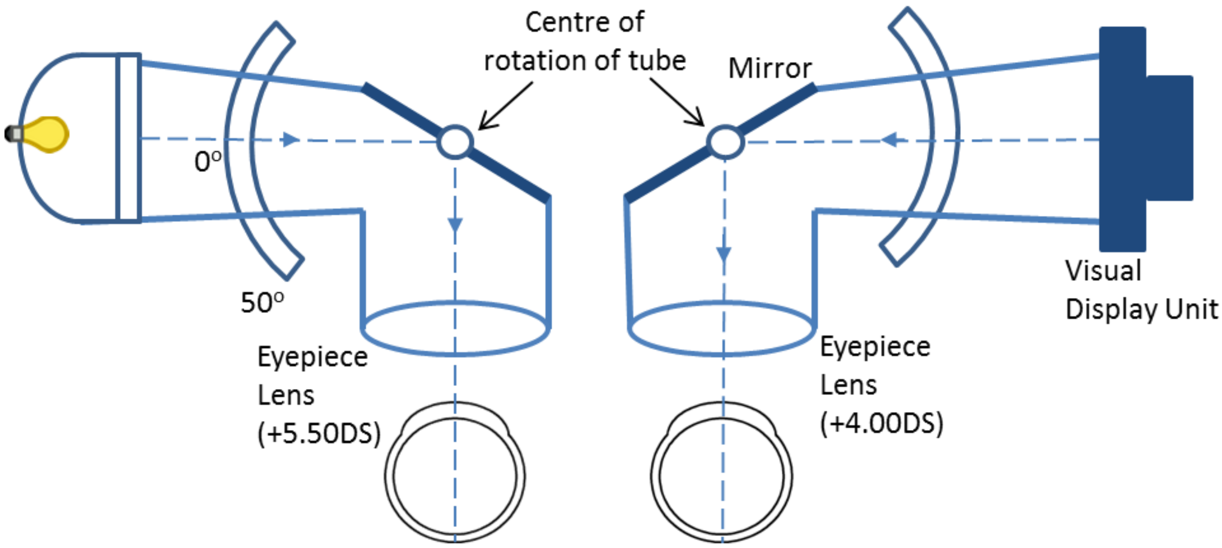


Figure 5.1: Left schematic; the traditional layout of the synoptophore components. A translucent slide with a picture painted on one side is placed in the slide holder, retro illuminated and viewed through the mirror. Note the differing Eyepiece lens powers, which account for the difference in distance from the stimulus plane to the eye.

Fusion

In order to determine the effect of fusional demand the positive vergence (convergence/base-out) range was used. The positive vergence range was chosen as it is least susceptible to change, especially of the recovery point. (70,71)

The objective angle of latent deviation was measured on the synoptophore using a custom fixation target in the design of a cross (with one red and one green line to each eye and a central smiley face fixation target (see figure 5.1.1)). The objective angle was fully corrected to establish a zero fusional demand condition. After establishing the subjective breakpoint by converging the tubes using the central ABB/ADD worm screw, the tubes were then diverged until a double image was reported by the subject. The recovery angle was noted and used as the fusional stress condition.

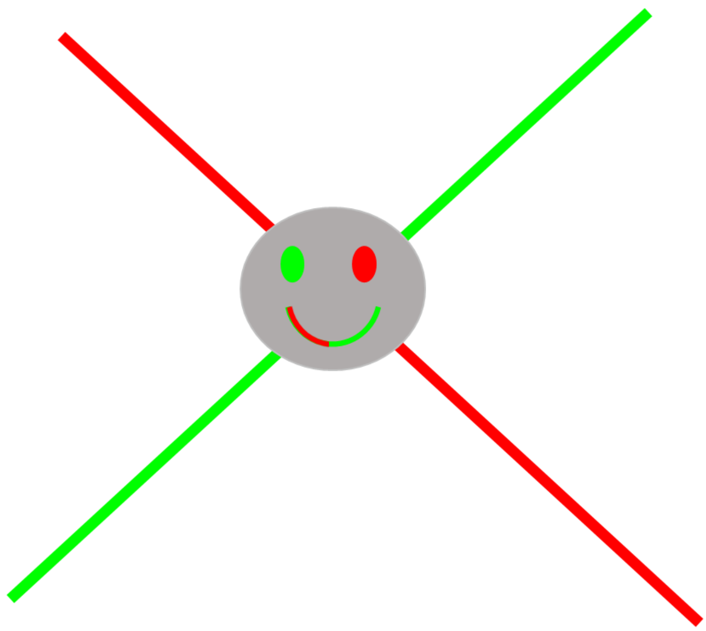


Figure 5.1.1: The 'Bagollini striations' type stimuli used to assess alignment and fusion on the Synoptophore. Red right eye, green left eye. If only one eye's view is perceived this indicates a lack of simultaneous perception. Pressing the

corresponding ‘cover test’ button on the Synoptophore occluded that eyes half image.

Stimuli.

A four alternate forced choice (4AFC) procedure was used, with the target random dot stimulus (presented with crossed disparity compared to the screen) and three distractor stimuli (presented with zero disparity) surrounding a central fixation target with a diameter of 0.76^{o} (36 pixels) (see figure 5.2). Within each condition, the three distractor stimuli differed from the target stimulus only in the difference of lateral positions of the left and right half-images. The fixation target acted as a feedback mechanism: green colouring indicated a correct response with red indicating an incorrect response. Each stimulus subtended 2.1^{o} (100 pixel square), wherein dots of 0.21^{o} (10 pixel square) were randomly distributed with a density of 25%. The stimuli were pre-computed using Matlab (Mathworks®) and presented on a grey background with an 89% Michaelson contrast and a mean luminance of 70 cd/m^2. The inner corners of each of the four stimuli were initially separated from the centre of the fixation target horizontally by 1.69^{o} (80 pixels) and vertically by 2.1^{o} (100 pixels). The maximum disparity level was 0.21^{o} (10 pixels) to avoid overlap of the left and right half-images of neighbouring stimuli. All stimuli were visible for a total of 1 second. This allowed the perception of smooth motion, while avoiding the perceived contrast reduction that can occur for rapidly changing patterns.

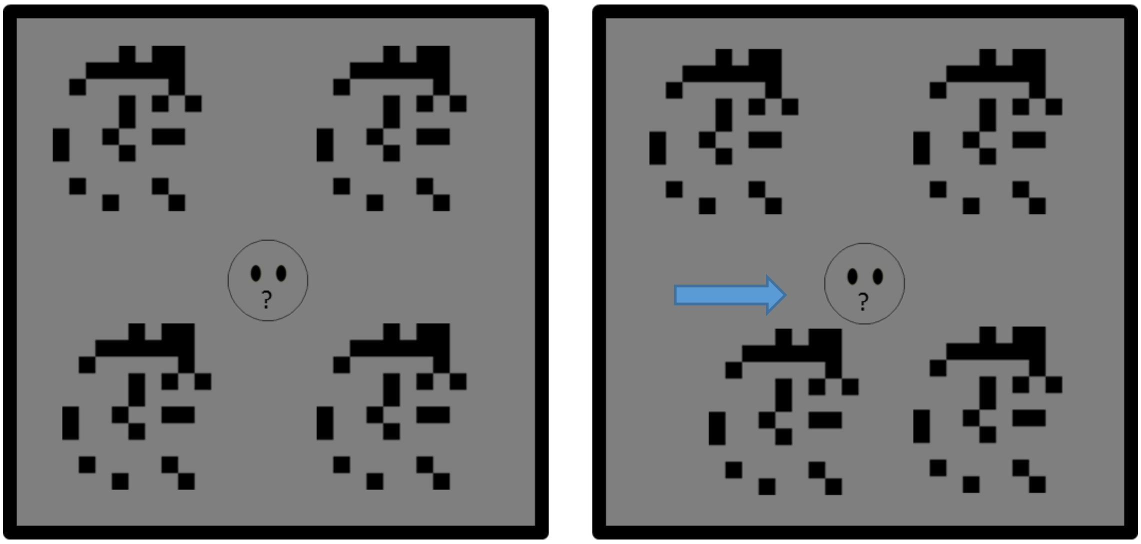


Figure 5.2: Schematic of stimuli viewed by participant. The left panel is presented to the left eye and the right to the right eye. As the lower left stimulus in the right panel has been displaced towards the fixation target, disparity has been created. If resolved this stimuli would appear forward of the fixation and control stimuli, closer to the observer.

To determine the contribution of changing z-location to the detection of depth, two stimulus conditions were included. In each condition, the appearance of the four stimulus patches on each trial was designed to be similar, aside from the target stimulus being defined by a separation of the right and left half-images.

1. **STATIC**. Target stimuli were presented with a fixed disparity. Both the stimulus' frontoparallel location and its dot pattern were constant throughout.

2. **Z-LOCATION CHANGE**. Target stimuli were presented with a disparity that changed over time (starting at zero and increasing towards the target disparity), with a constant location and dot pattern displayed. As these stimuli are seen to move laterally by some stereodeficient observers (due to

substantial suppression of one eye's input), to ensure that this percept could not be used to provide the correct answer in our 4AFC task, randomised rightward or leftward motion was added to the three distractor stimuli. The two half-images of each individual distractor stimulus moved simultaneously in the same direction and by the same distance as the target stimulus' half images.

Procedure

Once the equipment was adjusted for inter-pupillary distance, the subject's simultaneous perception (using the custom target), positive vergence range and any phoria was assessed on the Synoptophore using the target pictured in figure 5.1.1. The alternate cover test was performed using the buttons on the Synoptophore to correspond to a keyboard key press to remove the image presented to the corresponding eye. Fusion range was assessed using the fusion worm screw with both targets simultaneously presented (complete cross with smiley face control). The screw was turned to converge the tubes until the subject reported a double image, or the suppression of one eye (indicated by the perceptual loss of the complete cross/face). The tubes were then diverged until the complete, single percept of a face and cross returned. This was recorded as the 'recovery' angle.

A trial version of the experiment was run in order to familiarise the subject with the task, this involved completing a single staircase of the STATIC and Z-LOCATION CHANGE in habitual primary position.

The experiment was performed under standard clinical lighting conditions. The subjects received standardised instructions to maintain fixation on the central target, and to use a response box (formatted in the same layout as targets on the screen) to "choose the patch that appears closest to you in space".

The order of testing was balanced between the four conditions, STATIC Stressed & Unstressed, Z-LOCATION CHANGE Stressed and Unstressed.

Threshold estimation

A total of four variations were tested in a blocked format; STATIC or Z-LOCATION CHANGE in either with or without fusional stress. Three thresholds were estimated for each condition by separate staircases (Multistair handler functional of Psychopy), (21) starting at 0.08°, 0.06° and 0.004° respectively. The initial step size was 0.04°, which after one reversal reduced to 0.02°. After a further two reversals the step size was reduced to the minimum step size of 0.004°. A three-down-one-up method was used so that the staircase converged to a performance of 79.4% correct. (22) Thresholds were calculated as previous chapters.

Statistical Analysis

A 2x2 ANOVA was performed to examine the factorial combination of the two independent variables of depth (fixed/changing) and fusional stress (zero/recovery point). Only subjects who provided a reliable response in every condition were included in the ANOVA. Persons product moment correlation was performed to assess if any relationship existed between the variable angle of fusional recovery and stereoacuity levels with no fusional stress induced.

Results

In total, 72 subjects (50 Female, 25 male; mean (SD) age 22 (6) years) were assessed all of which completed the screening tasks successfully. Of these, 11 were excluded on the basis of unreliable performance in all conditions (see threshold estimation in methods). Visual acuity (mean(SD)) was -0.04(0.11) RE and -0.05(0.12) LE LogMAR. The amount of fusional demand induced (the recovery point) was between 1 and 26 prism dioptres (PD), with a mean (SD) of 8(6)PD. The number of subjects able to perform reliably in each condition varied, details and mean thresholds for the conditions are shown in table 5.1.

Table 5.1: Percentage of subjects who provided a reliable threshold in each condition (n=61) Mean(SEM) thresholds are provided in italics.

	STATIC	**Z-LOCATION CHANGE**
Zero Fusional Demand	67% *322"(53")*	61% *69"(23")*
Fusional Stress (recovery point)	66% *224"(40")*	74% *77"(21")*

Of the 61 subjects able to provide a reliable threshold in at least one condition, 21 were able to provide a reliable threshold in every condition tested and were included in the two way ANOVA (Figure 5.3). Thresholds were lower in the Z-LOCATION CHANGE conditions, confirmed by the presence of a statistically significant main effect of changing depth ($F(1,104)=8.23$, $p=0.005$). No main effect of fusional demand was found ($p=0.40$), as indicated by the similar thresholds for the two plots. The interaction between depth and fusional demand was not significant (p=0.44).

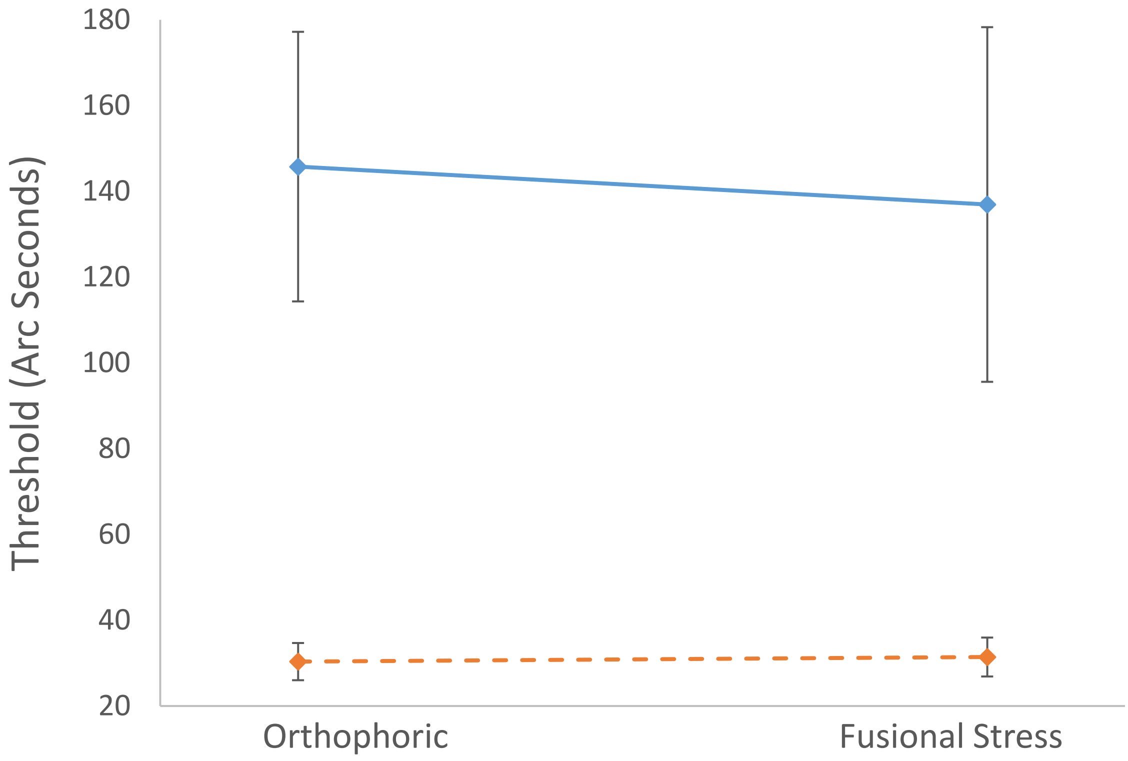
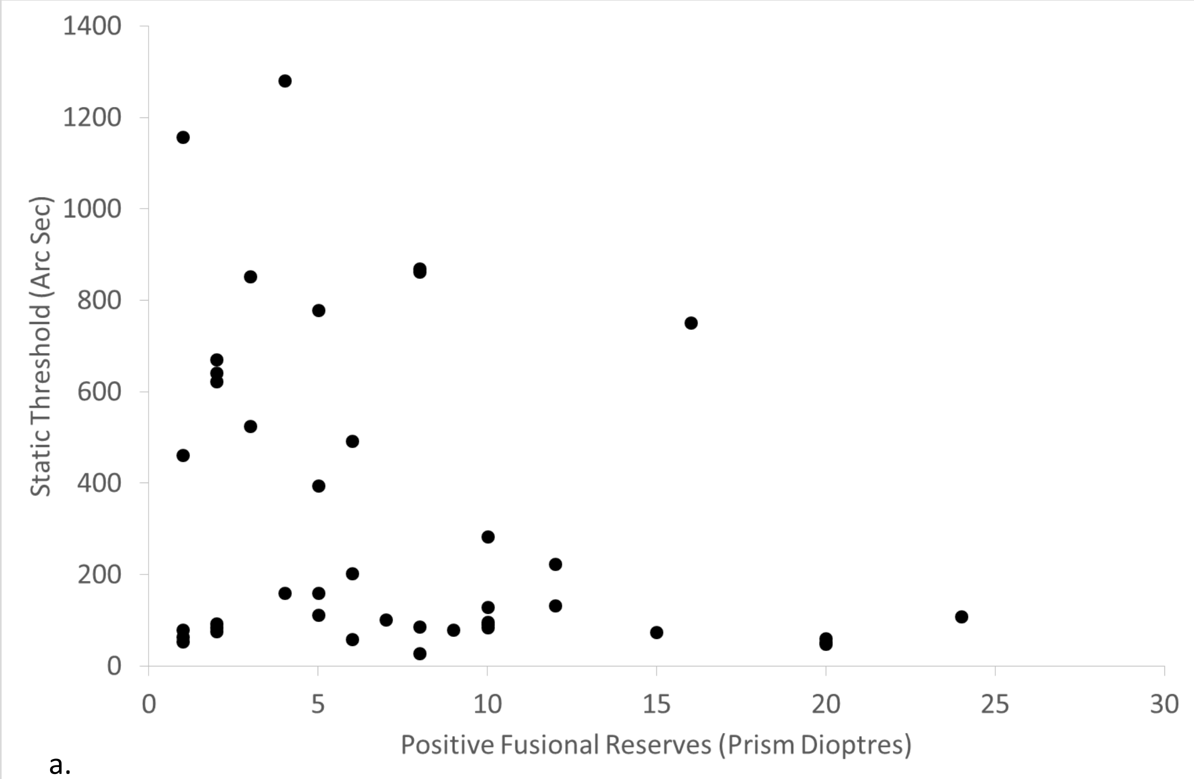
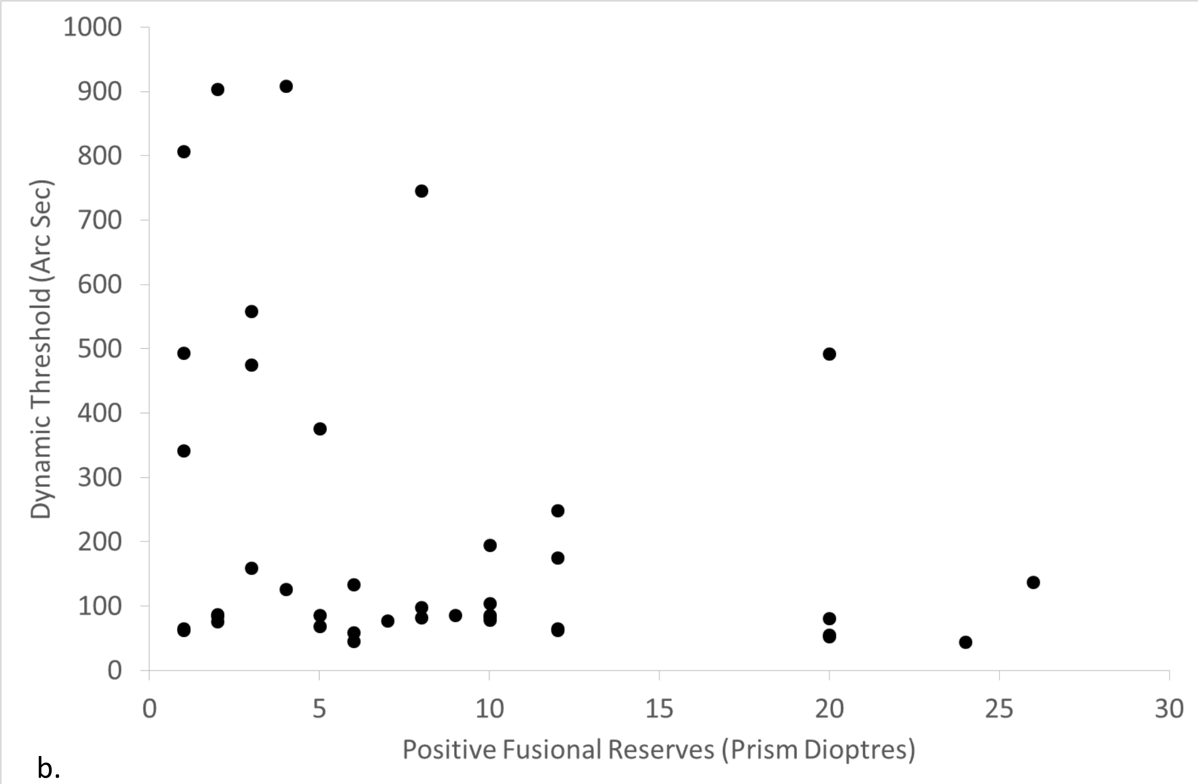


Figure 5.3: Factorial combination of disparity and pattern factors. Error bars represent ±1SEM, the solid line is the static condition and the dashed line is the dynamic condition.

To determine if the size of the fusional reserves available had any bearing on stereoacuity thresholds, Pearson's and Spearman's correlation was run between the size of the recovery angle and the static and dynamic stereoacuity thresholds with zero fusional stress (figure 5.4). No statistically significant difference from zero was found between the size of fusional recovery angle and stereoacuity, in both static and dynamic presentations (p>0.05).   If both axis are logged there is still no statistically significant relationship between variables in the static conditions, however there is a weak correlation (r=-0.33, p=0.04), suggesting that those with larger fusional reserves have better stereoacuity at baseline.



a.



b.

Figure 5.4: Plot of disparity detection thresholds (under zero fusional stress) versus positive fusional reserves available. a: Static condition (n=41) b: Dynamic condition (n=37)

Discussion

There is no statistically significant difference between stereoacuity thresholds in the fusional stress and zero fusional demand conditions, for both static and dynamic presentations. This indicates that fusional stress up to the recovery angle does not affect stereoacuity thresholds. Whilst the size of recovery angle varied in the population tested, the size of the recovery angle had no relationship with stereoacuity threshold measured; showing that as long as a phoria is well controlled, stereoacuity levels will not be affected by the fusional load. This supports the assertion by Worth (1901); if fusion is achieved, stereopsis is typically apparent, (60) and findings that stereoacuity is either normal or absent in intermittent exotropia. (72) We demonstrate that the presentations with changing disparity result in lower thresholds than static presentations, in line with previous findings (9,10,35)

Our results differ at first glance, to those found by Laird *et al.* where a 'reduced' level of stereoacuity was found in up to 92% and 56% of subjects tested with the FD2 and DR at the point where single vision occurred (the fusional recovery point). (66) The recovery point was much higher (median (IQR) 20(4) PD) than in the present study (mean (SD) 8(6) PD), which may be due to the differing methods used. Laird *et al.* used prisms in free space, where peripheral cues were available to aid fusion, whereas the current study used a dissociative central target (custom Bagollini striations on the synoptophore). When the study by Laird *et al.* was repeated encompassing the hysteresis effect (increasing the strength of prisms from nil up to 40 PD), fusion was maintained with good stereoacuity by all but one of the 20 subjects, until the first significant drop in stereoacuity to 200” by to 10% of subjects at 30 PD on the FD2 and 20% at 35 PD on the DR. A worsening of stereoacuity (from 60” to 100”) was reported earlier at 6 PD (FD2) and 16 PD (DR) for one of the subjects, but as previously noted, this worsening does not represent a real change in stereoacuity using these clinical tests. (67-69) The variation between subjects who demonstrated a reduction in stereoacuity and those who did not in these studies could be attributed to variation in the impact of fusional stress. Fusional stress of 10 PD may appear to be controlled by two individuals, but the demand on vergence systems may differ. The hysteresis effect may have been employed to achieve fusion at 10 PD by one individual with a recovery or re-fusion point of 8 PD, whereas the recovery point for another individual could be 20 PD. Both of these individuals were able to fuse 10 PD, but may provide differing stereoacuity results, based on fusional demands; the individual with a re-fusion point of 8PD would have less control at 10PD, than the individual that had good control up to 20 PD. The use of the recovery angle to introduce fusional stress in the present study, aimed to control these discrepancies, using a stable point relative between individuals.

The amount of fusional demand induced based on recovery points of the fusion range were between one and 26 PD. By comparing the size of recovery angle to the baseline stereoacuity, we determined that there was no relationship between the two. This further demonstrates that stereoacuity is unaffected by well controlled fusional demand.

As the amount of disparity increases during presentation in the dynamic condition, the effect of changing the stimuli position on the retina did not result in raised thresholds, in either the stressed or unstressed condition. This could suggest that it is unlikely that the visual system requires the ability to finely control ocular movements to maintain fine stereopsis as previously suggested, (61) however, it is possible that our participants were able to track the stimulus in depth via additional vergences movements, despite the 1s presentation time and fixation on the central target.

Another major factor that differed between this study and previous studies is the use of a computer controlled staircase procedure to determine stereoacuity level. In combination with the ability to present a higher number of disparity levels than available in book based clinical testing, the randomisation of the order of testing to avoid adaption bias (to the induced angle), any clinician bias and order of testing biases, the threshold measured is more reliable than that achieved with clinical testing. This allowed us to statistically compare the levels of stereoacuity directly, increasing sensitivity to any change in threshold.

These findings show that inducing stress to fusional control at the recovery limit of fusion does not result in reduced stereoacuity thresholds. Inducing fusional stress beyond this amount may result in a reduction of stereoacuity thresholds, however this would employ the hysteresis effect, which is unlikely to be accessible by individuals with intermittent distance exotropia, more likely in the case of decompensating phorias, where the limits of control are noticeably reached.

Chapter Six – Control experiments

Chapter six consists of a series of small experiments designed to investigate potential confounds within the main experiments. These are: the presence of spurious temporal correlations in the spatial correspondence only (CDOT) conditions, and differences in target patch speeds as a result of carrying the disparity level with a fixed presentation time. A further two experiments investigate the effect of varying the ratio of CDOT and IOVD cues present in the stimuli, including 'reconstituting' the isolated IOVD and CDOT cues.

Chapter 6a – Spurious Temporal Correlation

To isolate the CDOT or IOVD cues, stimuli have been designed to deliver a clear peak in the cross-correlation, either for spatial correlation between the eyes, or temporally in each eye, but not both.

In the case of an IOVD stimuli, spurious spatial correlations can occur which may contribute to an improvement in threshold. (2,38) The inclusion of these random correlations are unavoidable in the IOVD stimuli, as the stimuli pattern must be constant in order to preserve temporal correlation between the eyes. However, any spurious spatial correlation would appear as a 'cloud' of disparity, of both crossed and uncrossed configurations, with no clear signal to depth. The findings of chapter four show the largest thresholds (if achieved at all) are recorded for the IOVD condition (CONTROL), with the CDOT only cue providing lower thresholds (Z-

LOCATION + PATTERN CHANGE). This suggests that the presence of spurious spatial disparity signals were not informative to the detection of depth.

The findings of chapter four however, also show that the lowest thresholds achieved are in the Z-LOCATION CHANGE only conditions, where both CDOT and IOVD cues are present. As we show that a pattern change has no significant effect on depth detection thresholds, the presence of the IOVD signal may contribute to the lower thresholds recorded. It is possible that spurious temporal information is included in the Z-LOCATION + PATTERN CHANGE stimuli, as well as other CDOT stimuli used in other studies. (73) It is speculated that because the CDOT signal appears to be more powerful than the IOVD signal (lower thresholds), (2) any spurious temporal correlations won't have an effect.

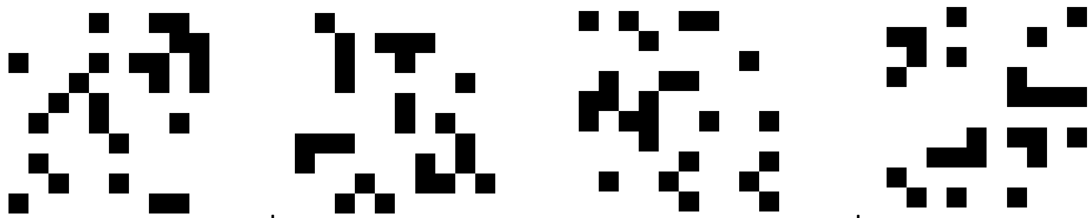
The aim of this chapter is to investigate whether any spurious temporal correlations improve an individual's disparity detection threshold, by comparing a CDOT stimuli, to a CDOT stimuli where the potential for temporal correlation is eliminated. As any signalled temporal change would be larger at a closer viewing distance the comparisons were repeated at 3m and 1.5m.

Materials and Methods

Stimulus Design

Each pattern consisted of 25 black dots arranged in a 10 by 10 grid, with each grid subtending 0.5°. The dots subtended 0.05° and were randomly distributed in one set of the stimuli (CDOT Random).

In the second set of stimuli the dot patterns were permutated (CDOT Controlled) to eliminate any temporal correlation by avoiding consecutive presentations temporally (figure 2). If the same dots (e.g. the black dots in figure 6A.1) were presented at time 1 and time 2, both CDOT and IOVD cues would be present. If a new permutation of dots, where zero dots could appear in the same location as previously presented were displayed at time 2, no temporal correlation would occur. The only possible consecutive temporal presentation would be of zero change in spatial location, which would signal zero change in depth location.



a b c d

Figure 6A.1: An example of the CDOT controlled stimuli. Each letter (a to d) shows a different permutation of the 25 dots.

Procedure

The procedure used was similar to previous chapters, however the CDOT controlled stimuli only allowed for four unique permutations; therefore, the 4th version was followed by the 1st and 2nd again. The experiment ran using the multistair handler function of psychopy, with two staircases running for each, one starting at a large disparity and one at a small disparity. The targets were designed to occupy the field of foveal fixation, the central 4^{o} of the visual field. As testing was carried out at 3m and 1.5m the stimuli sizes were adjusted accordingly.

The subjects received standardised instructions to maintain fixation on the central target and to use the response box formatted in the same layout as targets on the screen, to choose the patch which appeared closest to them in space.

Apparatus

As previous chapters using the LG screen.

Threshold estimation

Staircase implementation and threshold estimation were as described in the main methods chapter.

Statistical Analysis

To assess the significance of any difference between the two CDOT variations, a two way ANOVA was used to determine the effect of Controlled vs Randomised dot pattern generation, and the effect of testing distance.

Results

A total of 43 subjects were recruited aged between 17-56 years with 13 male and 30 female, of these, seven subjects were excluded on the basis of unreliable results. All subjects had visual acuity of driving standard or better in both eyes and scored 140 seconds of arc or better on the stereo fly test.

There is no statistically significant difference in stereoacuity threshold between the two CDOT variations (p=0.55) or the two testing distances (p=0.95), nor is there any significant interaction between the factors (p=0.89) (figure 6A.2).

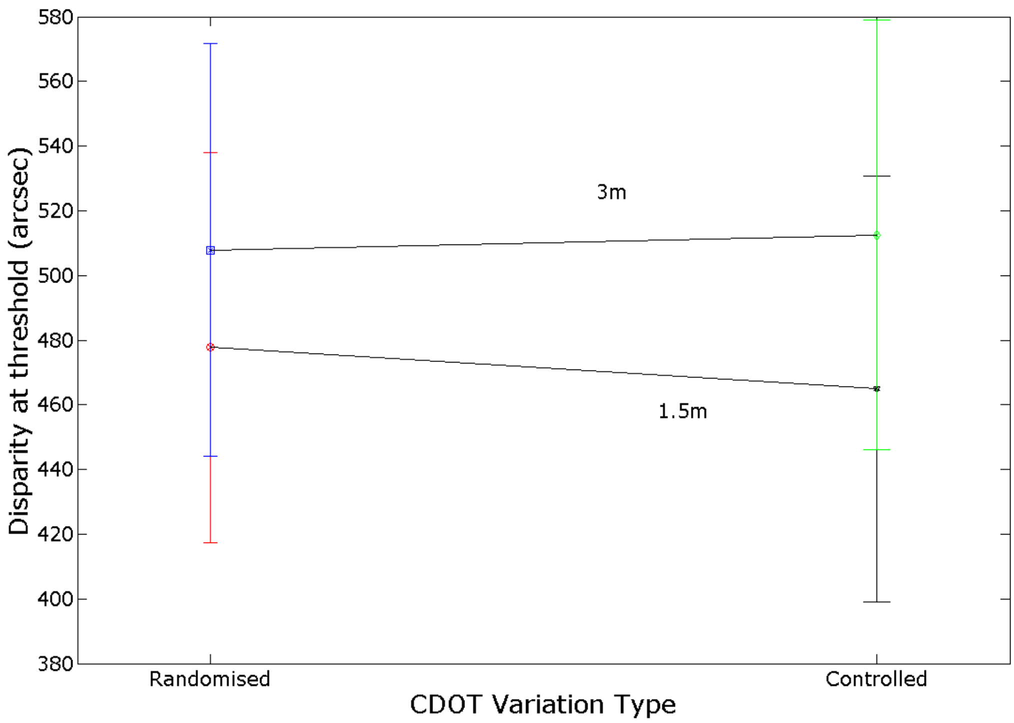


Figure 6A.2: Disparity thresholds for the Random and Controlled patterns of the CDOT stimuli and testing distances. There is no statistically significant difference in any threshold level.

To determine the amount of spurious spatial correlations which may have occurred in the CDOT Random stimuli used in the experiment, the entire set of 60 images used at 3m and 1.5m were compared. Each element of the ten by ten grids was counted, for the number of times it appeared as a signal dot (figure 6A.3). Each element in the grid has the probability of appearing as a signal dot of 25%. In the stimuli set used, based on the observations in figure 6A.3, the probability of each element being common as a signal dot is between 45% and 80%. Therefore the probability that each element is presented as a signal dot is between 11% and 20%. The probability of one consecutive presentation is between 1% and 4%, with the probability of six consecutive presentations between 6.4^{x10-5} % and 1.77^{x10-6} %.

34	36	33	45	33	39	35	37	41	33
42	46	40	37	41	38	45	33	42	33
37	40	42	40	38	32	33	40	37	41
41	32	36	34	39	37	35	29	36	32
41	34	31	35	39	39	32	42	40	37
35	31	35	43	39	29	41	33	37	45
39	43	41	39	43	36	31	29	34	39
23	38	33	45	35	43	39	36	40	36
36	31	39	40	39	35	41	40	45	33
38	36	37	41	48	37	39	43	37	31

Figure 6A.3: Frequency of each cell containing a signal dot in entire stimuli set n=60.

As the recognition of motion in depth is improved in many individuals when IOVD is present(2,3) the subjects were divided into those who performed better with the presence of IOVD and those who performed better in the absence of the IOVD cue. There was no significant difference found ($p>0.15$) between these groups at 1.5m or 3m.

Discussion

This experiment suggests that any spurious temporal correlations that randomly occur during the generation of stimuli for the isolation of changing disparity over time, do not provide an additionally useful cue for the extraction of depth information. Whilst the presence of spurious spatial correlations in the display of interocular velocity difference stimuli have been previously described as a beneficial for the recognition of motion in depth, it appears that any random appearance of a temporal cue in a changing disparity over time stimuli has no significant effect.

These data show that there is no significant effect on stereoacuity threshold of varying test distance between 3m and 1.5m. Whilst the difference in accommodative demand is only +0.50DS and the closer distance is not considered a 'near' test, it is still within the range of the Frisby Stereotest™, which is considered a 'near' vision test (range of 0.3 to 1.5m). The Frisby test tends to provide a threshold of 15" higher than the distance version, the FD2, (46) and whilst this may be attributed to the limited testing range of the FD2, the tests also differ in their design. The Frisby test is a location identification task, with the disparity target circle defined by a number of small shapes (multiple boundaries), the other is a shape identification task, with the disparity target a solid shape with only one boundary. The assessment of threshold stereoacuity used in this study was identical in design for each distance tested; include the size of the test stimuli, which was kept consistent with testing distance. Whilst the distances tested were limited, and with the changes in distance unlikely to affect any underlying binocular alignment problems, these data suggest that stereoacuity thresholds do not vary over distance.

Previous studies have shown that stereoacuity thresholds increased as viewing distance decreased from 57cm to 28.5cm, a limit which the authors attribute to a minimum physical depth, based on the high-level combination of multiple depth cues. (74) Other authors consider this data further and discuss that stereoscopic thresholds are elevated in the presence of vergences variability and fixation disparity, (75) at first glance, in contradiction to my findings in chapter five. However, the effect of thresholds increasing with a close viewing distance appears only to have an effect below 57cm. Indeed, this is supported by earlier work which demonstrated no change in stereoscopic acuity beyond 50cm. (76) These studies support the finding of no effect of varying test distance between 150 and 300cm.

The probabilities discussed in the results section, are directly applicable to the 'random CDOT' stimuli used in the experiment, which were generated using the uniform distributer pseudo-randomisation function of MATLAB, however, the probabilities will apply to other randomly created stimuli (using the default random number generator seed). Given the uniform nature of the randomisation function, it can be concluded that the presence between two frames of 1% to 4% of temporal correlation is insufficient to benefit the detection of motion in depth. Even if these percentages of the IOVD cue benefited the detection of motion in depth, the probability of temporal correlation across numerous frames is highly improbable.

It is possible that the population tested were insensitive to the IOVD cue to depth, as it has been previously shown that individuals can have a bias towards being able to use a particular cue. (2) This is further supported by the results of chapter four, which shows that out of 127 subjects only 11 were able to perform reliably in this condition, with the majority only providing the ceiling value as threshold level.

Chapter 6B – Rate of change of disparity

The rate of disparity change, or equivalently the speed along the z-axis, varied in all previous experiments depending on the target disparity level of the trial being tested. The presentation time was always fixed at 1 second, therefore all changes in z-position had to occur within this time resulting in a range of speeds; the larger the disparity the more rapid the change in depth. There are situations in which the CDOT and IOVD mechanisms might differ in their utility; it has been suggested that IOVD is an important cue for speed discrimination. (3,77-79) This however is suggested to favour higher speeds of motion in depth, of above 1800” per second. (73) The maximum thresholds tested in the one second presentation time were 543”, which suggests that any effect should not be marked.

To assess this effect an experiment was designed to determine if the rate of change of disparity (Z-location change) determined depth detection thresholds.

Materials and Methods

Ethical approval and inclusion/exclusion criteria were as previous.

Apparatus

As Previous

Stimuli

The experiment included two main conditions, an isolation of the CDOT cue (CHANGING DISPARITY, CHANGING PATTERN – see chapter 4) and an isolation of the IOVD cue (CONTROL – see chapter 4). Each of these were tested at four different speeds (rate of Z-location change); 450, 900, 1800 and 3600 arc seconds per second. The lack of binocular correlation means that there is no coherent disparity in the IOVD condition, which should make a depth identification task impossible. However, the dots of the stimuli on the left and right retinae move in the same way as they would in the CDOT conditions to reach their target relative displacement, so the rate of change and displacement will be considered analogous. An important difference in this experiment is that the number of stimuli patches/changes in on screen disparity was halved to three instead of the six used in the rest of this thesis.

Threshold estimation

Three staircases were run for each of the speeds within conditions; one starting with a high (1692”), medium (1354”) and low (1015”) disparity. Step sizes for the eight reversals were in order 846”, 846”, 338”, 338”, 169”, 169”, 169” and 169”. A three up-one-down procedure was used;(22) after three consecutive correct responses the disparity level was decreased, after one incorrect response the disparity level was increased. A total of eight reversals were required for each staircase to end. If after 150 trials, the required number of reversals were not met an interval was offered to the subject. The conditions were blocked in relation to either containing the CDOT or IOVD only, but the three staircases and different speeds were interleaved randomly.

Procedure

At all times, subjects wore their habitual correction appropriate for distance underneath the polarising glasses with the +3.00 DS add.

Statistical Analysis

To assess the significance of any effect of speed on depth detection thresholds, linear regression was used. The same inclusion and psychometric fitting procedure was used as in all previous experiments.

Results

A total of 44 subjects were tested, (14 males, 30 females) aged mean(SD) 20(3.7) years. The mean (SD) VA difference between eyes was 0.08(0.08) LogMAR, with an mean(SD) stereoacuity screening score of 44”(9).

IOVD condition

For the IOVD only condition, 14 subjects were able to provide a reliable threshold in at least one speed. The demographics of these subjects did not differ from the main cohort, 4 males and 10 females, Age 20(3.3) 18-28 years, mean(SD) VA diff 0.07(0.07) LogMAR, and stereoacuity of 44”(11).

Table 6B.1: The number of subjects able to provide a reliable threshold in the IOVD condition

Speed	450” per second	900” per second	1800” per second	3600” per second
Number able to provide a reliable threshold	12	8	5	5
Percentage of subgroup (n=14)	86%	57%	36%	36%
Percentage of all tested (n=44)	27%	18%	11%	11%
Threshold of those with reliable threshold	2015”	2373”	1030”	2747”
SD	1359”	1665”	641”	1647”

Of these 14 subjects, only two were able to provide a reliable threshold at all speeds in the IOVD condition, which did not allow formal statistical analysis to be performed. Figure 6B.1 shows the thresholds for these subjects.

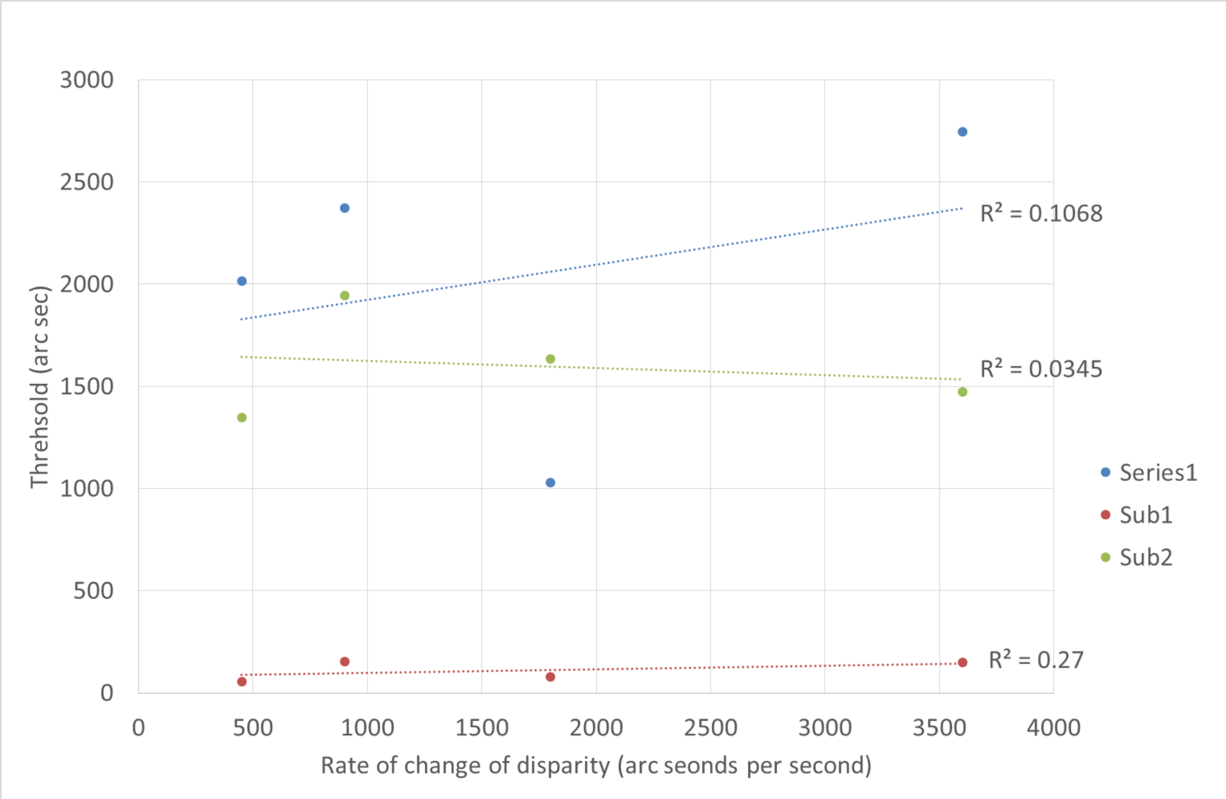


Figure 6B.1: Plot of thresholds for subjects 1 and 2 who could perform reliably in all conditions. Series1 is a plot of the mean threshold of those who performed reliably under this speed (provided for indication of potential pattern only as each average has a different number of subjects included in each threshold – see table 6B.1).

CDOT condition

For the CDOT condition, 31 subjects were able to provide a reliable threshold in at least one of the speed conditions. The group consisted of seven males and 24 females aged mean(SD) 22(4.2) years, with an average VA difference between the eyes of 0.09(0.09) LogMAR. Stereoacuity of this group was 44”(11) as measured by the stereofly test.

Table 6B.2: The number of subjects able to provide a reliable threshold in the CDOT condition

Speed	450” per second	900” per second	1800” per second	3600” per second
Number able to provide a reliable threshold	23	27	22	18
Percentage of subgroup (n=31)	74	87	71	58
Percentage of all tested (n=44)	52	61	50	41
Threshold of those with reliable threshold	1220”	1999”	2049”	2095”
SD	926”	1311”	1538”	1573”

Of these 31 subjects, ten were able to provide a reliable threshold at all speeds in the CDOT condition, however there was clear hetroscedasticity present in the form of an increasing funnel as speeds increased (Figure 6B.2). To correct for this a log transformation was performed (figure 6B.3).

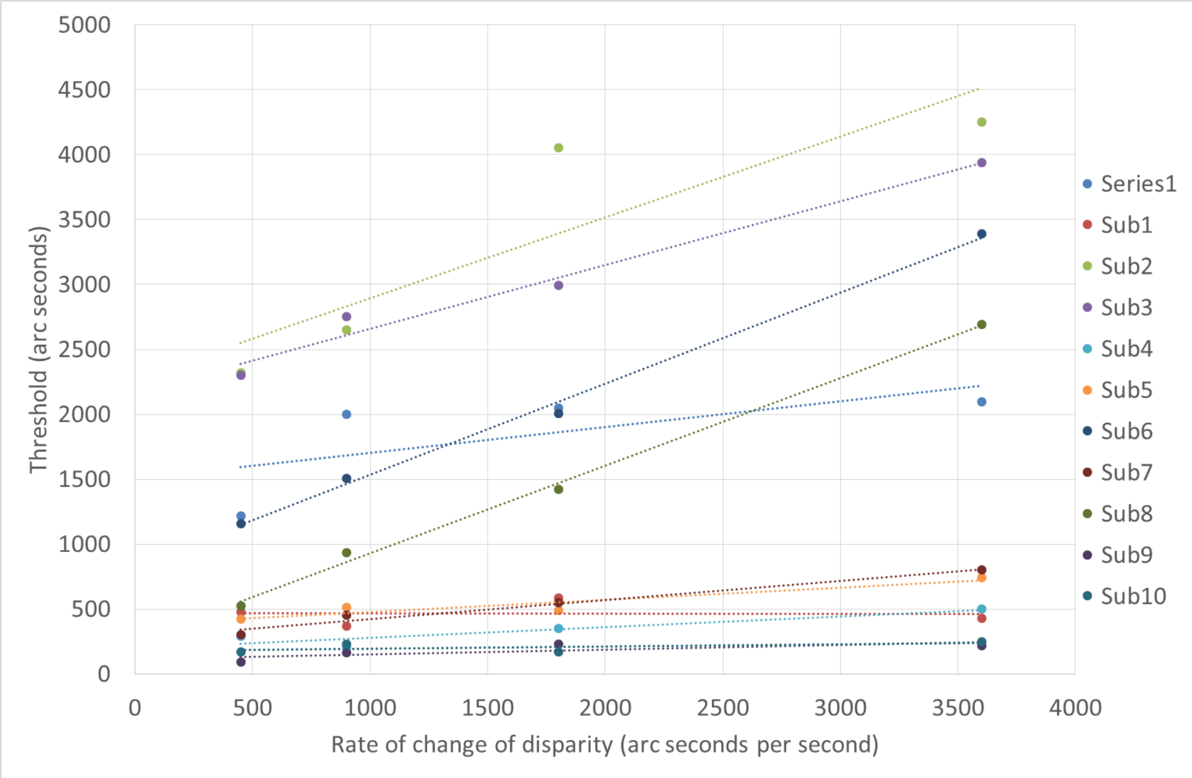


Figure 6B.2: Plot of thresholds for subjects who could perform reliably in all conditions. Series1 is a plot of the mean threshold of those who performed reliably under this speed (provided for indication of potential pattern only as each average has a different number of subjects included in each threshold – see table 6B.2).

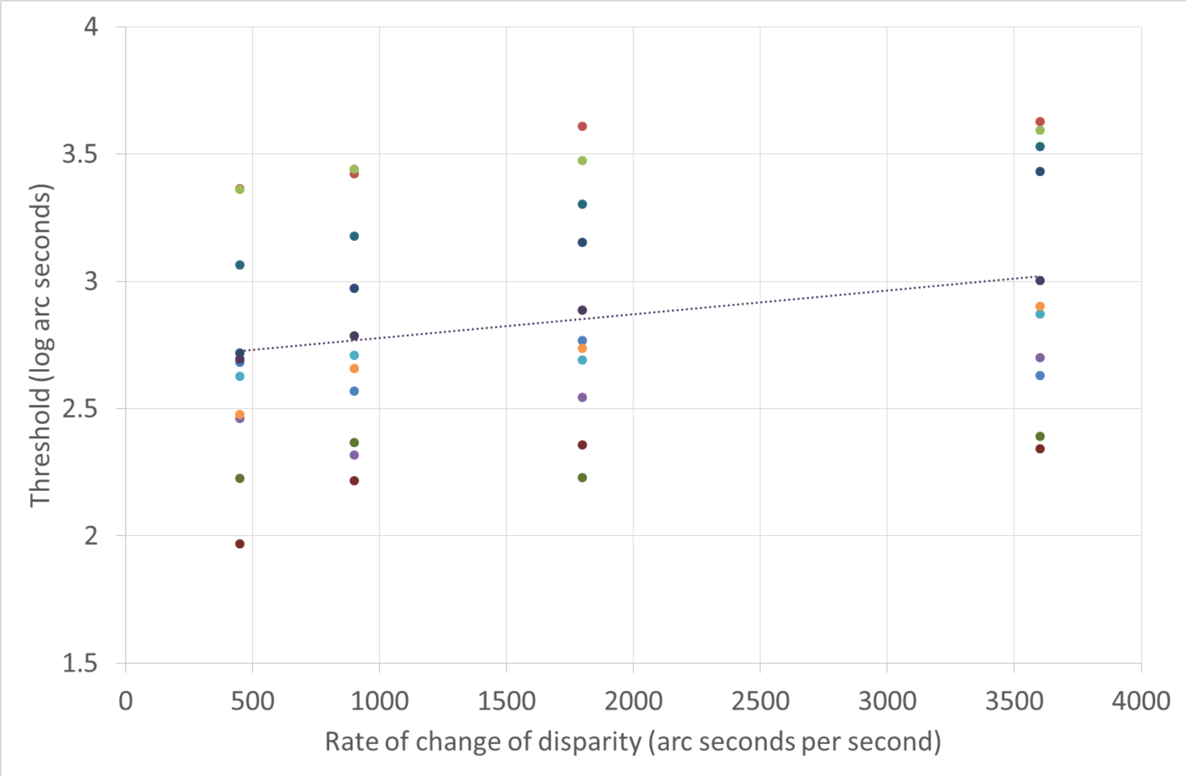


Figure 6B.3: Plot of Log thresholds for subjects who could perform reliably in all conditions. The dotted line represents the regression line.

The regression equation was: Threshold = 2.686 + ($9.24X10^{-5}$ X rate of change of disparity). A linear regression established that the rate of change of disparity could not statistically significantly predict depth detection thresholds, $F(1, 39) = 2.357$, $p=0.133$.

Discussion

This experiment demonstrated no effect of the rate of change of disparity on threshold, and confirmed previous findings of lower thresholds in the CDOT condition versus the IOVD condition. These results are limited however by the small number of participants able to perform reliably in all conditions. There are a number of unique features in this experiment compared to previous chapters that may have contributed to a low rate of reliable response.

The close proximity of the screen, and reduction to three from six different patterns/on screen disparities was necessary as the screen refresh rate was limited to 60Hz. This close proximity, even with the provision of optical correction, was anecdotally uncomfortable for the participants and may have reduced concentration during testing. Any subject with a weakness of convergence may have found this task especially difficult. It is unlikely that reducing to three presentations would have an impact on the perception of depth, as with only two frames, the percept is clearly recognisable. (1,2)

As a greater amount of the participants' visual field was taken up by the display, (even though all experiments were performed in darkness) peripheral fusion may have been hampered by the lack of cues. This was also the case in chapter five, as only central fusion was employed when using the synoptophore. However chapter five did show that even under duress from fusional stress, stereoacuity levels are unaffected.

The rate of change of disparity varied over a relatively small range. Slower speeds were assessed during the pilot phase of this experiment, but the length of the trial was deemed too long. Faster speeds were not possible due to the low refresh rate of the display used in all experiments.

It is possible that participants were blind to stereo motion, however, stereo motion suppression, if an issue, would only effect small disparities near threshold. The faster speeds present at the higher thresholds in chapter four (543” per second) would be most likely to benefit the IOVD condition. However only a small number of the respondents in chapter four were able to provide a reliable threshold (many at 543”). Even if it were the case that higher speeds increases the utility of the IOVD cue, in this experiment, the greatest number able to perform reliably were in the slowest IOVD condition.

These findings suggests that depth detection thresholds are not affected by the speed of presentation. It is unlikely that the variations in speed would have had any impact on the results of the previous experiments in the previous chapters.

Chapter 6C – The ratio of cues

Experiments that aim to investigate the cues to motion in depth, isolate the unique features of each, namely disparity only, and motion only cues by rendering one source of information noninformative. To isolate the CDOT or IOVD cues, stimuli have been designed to deliver a clear peak in the cross-correlation, either for spatial correlation between the eyes, or temporally in each eye, but not both.

These are described in various ways with the cue to changing disparity over time investigated using Dynamic Random Dot Stereograms (DRDS) – that is our CHANGING Z-LOCATION, CHANGING PATTERN stimuli. The stimuli are identical in that the elements defining successive frames do not contain the same pattern of elements as previously displayed. In terms of dots, the dots are randomly reordered to a new spatial location. This cue is not common in nature except where elements of a lager object would change in configuration, such as in a swarm of bees moving through depth whilst changing lateral location (ignoring any change in element size).

The interocular velocity difference cue, investigated using Time Correlated Random Dot Stereograms (TCRDS); an example used is the CONTROL condition in chapter four. The elements of the stimuli are presented to only one eye, so in a pattern of 26 dots 13 are presented to the right eye, and a different 13 are presented to the left eye. The pattern remains constant. Again this in not a common cue in isolation in nature as the overlapping of visual fields would need to be prevented, e.g. viewing a large object moving toward or away from the observer, from behind a pillar such as a scaffolding pole.

The use of the cues is isolation have been clearly demonstrated, but the lowest thresholds are always found when both cues are present. This condition is referred to as dynamic random dot (DRS) in the literature, and the condition we refer to as CHANGING Z-LOCATION. It is the most ecologically valid cue investigated as both cues are presented by the same elements of an object approaching in depth, without the inclusion of monocular cues such as looming.

Throughout all previous chapters, the lowest depth detection thresholds have always been achieved in the COMBINED condition with both cues present. The aim of this experiment is to compare the depth detection thresholds of conditions where the ratio of CDOT and IOVD cues are varied are varied to the COMBINED condition.

Materials and Methods

Ethical approval and inclusion/exclusion criteria were as previous. The data were collected by second and third year undergraduate students as part of a research project.

Stimuli Design

Part one

Experiment one consisted of seven different conditions. The three baseline conditions were: CHANGING DEPTH (CDOT + IOVD), CHANGING PATTERN, CHANGING DEPTH (CDOT only) and CONTROL (IOVD only) – (for full description see chapter four). Four different ratios of IOVD to CDOT were included 16% IOVD, 48%

IOVD, 64% IOVD and 80% IOVD, with the remaining percentage consisting of the CDOT cue.

The same number of dots used in the previous experiments (25) were used, which limited the design to the above ratios to permit the use of whole dots only. Depending on the condition, the dots used for each element were split between containing the CDOT and IOVD cue only. For example, in the 48% IOVD condition, 12 dots are split between the left and right eye to signal the IOVD cue whilst the remaining 13 dots define the CDOT cue. (see figure 6C.1) The CDOT cues consist of four permutations that do not overlap with any successive IOVD or CDOT dot position, as detailed in chapter 6A. These dot patterns were precomputed in Matlab.

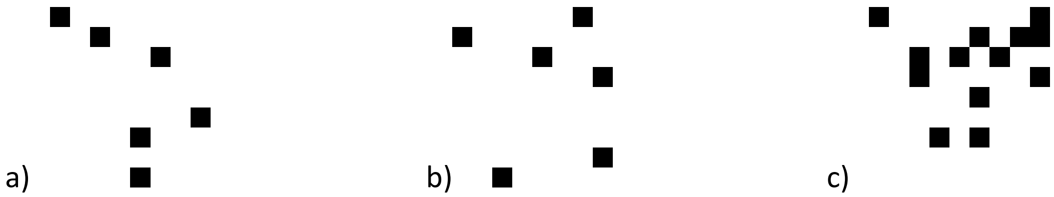


Figure 6C.1: Example stimuli patterns for the 48% IOVD condition. a) IOVD left half image (6 dots), b) IOVD right half image (6 dots) and c) CDOT left and right half image (13 dots)

Part two

Due to the inclusion of only 25 dots in part one, a condition where exactly half the dots signalled the IOVD and CDOT cues were not possible. To address this, this part of the experiment used 28 signal dots per condition. Baseline conditions of CDOT and IOVD were used, but consisting of 28 dots. A RECONSTITUTED condition of 14 dots of IOVD and 14 dots of CDOT cue (the 50:50 condition missing from part one) was created as the main comparison to the DEPTH CHANGE conditions. Three versions of the DEPTH CHANGE condition were created, one with 28 dots, one with 14 (to contrast if only the CDOT cue were used) and one with seven dots (to contrast where only the IOVD cue may be used. The generation of the stimuli patterns were as in part one.

Procedure

The stimuli only had four unique iterations so the 1st and 2nd were used for the 5th and 6th frame.

The subjects received standardised instructions to maintain fixation on the central target and to use the response box formatted in the same layout as targets on the screen, to choose the patch which appeared closest to them in space.

Apparatus

LG Screen as previous

Results

Part one

A total of 51 subjects were recruited for this study, but only 13 subjects were able to provide a reliable threshold in at least one condition. The 13 subjects were aged mean(SD) 22(6) years, with a mean(SD) visual acuity difference of 0.06(0.06) LogMAR (ETDRS). The mean(SD) stereoacuity was 43”(11”) measured using the Titmus circles. The details and depth detection thresholds achieved by these subjects are shown in table 6C.1.

Table 6C.1: Depth detection threshold and number of subjects able to provide a reliable threshold for each condition (from n=13).

	IOVD	DEPTH CHANGE, PATTERN CHANGE (CDOT)	DEPTH CHANGE	16% IVOD	48% IOVD	64% IOVD	80% IOVD
Number able to provide a reliable threshold for the condition	7	7	10	5	5	2	6
Mean Depth Detection Threshold	129”	100”	99”	254”	327”	376”	369”
SD	132”	75”	60”	335”	265”	80”	252”

Of these 13 subjects only two were able to provide a reliable threshold in all conditions. The thresholds measured are shown in figure 6C.1.

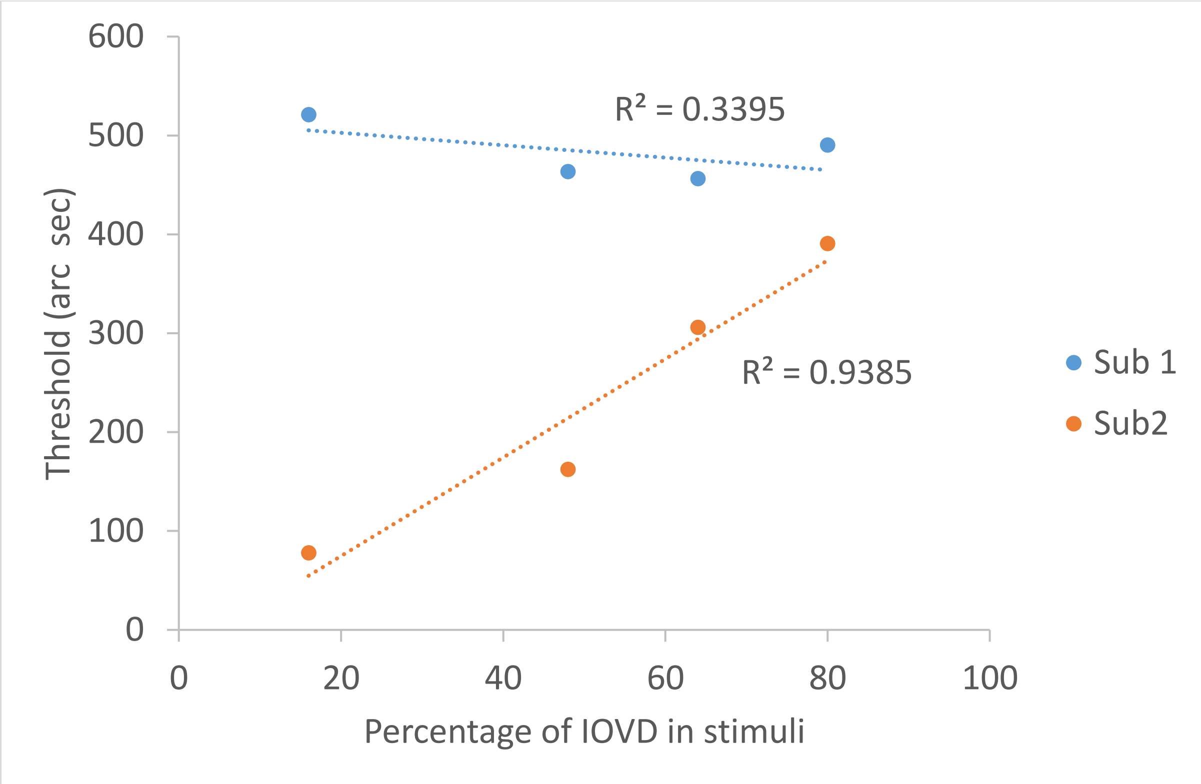


Figure 6C.1: Plot of thresholds of the two subjects who could provide a reliable threshold in all conditions.

With an n of two, any regression model has no explanatory power (F(1,6) = 0.78, p = 0.412).

Part two

A total of 41 subjects were tested with 14 able to provide a reliable threshold in at least one condition. The 14 subjects were aged mean (SD) 22(4) years, with a mean (SD) visual acuity difference of 0.06(0.05) LogMAR (ETDRS) between eyes, mean (SD) stereoacuity was 44”(8”) Titmus circles. The number who could provide a reliable threshold and the depth detection threshold achieved are shown in table 6.2.

	DEPTH CHANGE 28	DEPTH CHANGE 14	DEPTH CHANGE 7	RECONSTITUTED CDOT + IOVD	IOVD Only	CDOT Only
Number able to provide a reliable threshold	8	8	9	3	3	3
Mean Depth Detection Threshold	162”	230”	199”	232”	298”	69”
SD	144”	53”	35”	93”	113”	36”

Table 6C.2: Mean (SD) depth detection thresholds for each condition. n=14

There is no significant difference between the three DEPTH CHANGE conditions; the variation in signal strength has no effect on threshold. Of these 14 subjects, only one was able to provide reliable thresholds in all conditions, as shown in table 6C.3. This subject was the only experienced observer included.

DEPTH CHANGE 28	DEPTH CHANGE 14	DEPTH CHANGE 7	RECONSTITUTED CDOT + IOVD	IOVD Only	CDOT Only
20”	19”	25”	173”	20”	14”

Table 6C.3: Mean (SD) depth detection thresholds for each condition for one subject

Discussion

The aim of this experiment was to compare the depth detection thresholds of conditions where the ratio of CDOT and IOVD cues are varied are varied to the COMBINED condition. Consistent with previous experiments, the conditions with a fixed pattern and changing disparity led to the lowest thresholds on average.

Too few subjects were able to provide a reliable response in all conditions, preventing formal statistical analysis. The subjects who provided a reliable response also showed variability in which cue they utilise the most, subject 2 in figure 6C.1 and the subject in table 6C.3 appear to favour stimuli with more of the CDOT cue present, showing some increase in threshold when IOVD is present. Subject 1 in figure 6C.1 appears to show some utilisation of the IOVD cue as thresholds improve when the amount of CDOT present in the stimuli decreases. This variability in the use of cues is common, and has been demonstrated previously by other authors. (1,2) These results demonstrate that it is more difficult to reliably discriminate depth in the reconstituted conditions when each signal dot only contains a single cue. In the reconstituted condition, the same total amount of each cue is present to define the stimulus patch and therefore to imply the edges of the patch. These result suggests that individuals do not respond to the implied edges of the patch to detect depth, and must rely on the cue provided by the signal dots. This finding lends confidence that the results of chapters three and four are due to the isolation of the cues, and are not due to the implied edges providing an undesirable spatial and/or temporal cue.

The clearest results in this experiment come from experienced, practised observers (who expectedly appear to favour the CDOT cue for the detection of depth). This, combined with the low number of subjects able to perform this experiment, favours investigation in trained and practised observers, rather than the naïve population tested. Some complication may have been introduced through using undergraduate students to collect the data, however as the instructions for the experiment were displayed by the programme, this should have been consistent across all individuals.

For the lowest thresholds, the two cues to motion in depth must be present in the elements defining the stimulus patch, and not separate elements defining the same patch.

Conclusion

These control experiments suggest that the findings of the previous chapters are robust and cannot be explained by the presence of spurious temporal correlation in the CHANGING PATTERN, CHANGING DEPTH (CDOT) cue, or the variation in speed between different levels of disparity. The final control experiment shows that the task to detect depth is not reliant on the implied edges of the patch, which theoretically contain both cues.

Chapter Seven - General Discussion

Summary

There are anecdotal and qualitative reports of 3D depth being revealed when viewing entertainment media such as 3D films at the cinema, to those who are not clinically expected to perceive it. (30,80-82) The aim of this thesis is to quantitatively test these findings. Stimuli were designed to isolate any monocular cue to depth, to ensure that binocular processing was necessary to determine the presence of depth. Further, the dynamic nature of 3D films include stimuli that move across the screen as well as through depth, necessitating investigation. The preceding chapters have presented evidence, to support the idea that depth is more easily identifiable in the presence of motion.

By systematically isolating the characteristics of dynamic stereoscopic stimuli it has been demonstrated that for some dynamic stimuli, depth detection thresholds are lower than for static stimuli, common across many observers. The specific dynamic facet which leads to lower thresholds is a change in z-location, which is movement through depth towards the observer as demonstrated in chapter three and chapter four. Chapter six shows these findings are unlikely to have been contaminated by spurious temporal correlation, variation in distance, or variations in speed of z-location change during stimulus presentation. Chapter six also showed that if the two cues to motion in depth were present in the stimuli, but defined by different dot elements the threshold of depth detection was much higher than if a single element contained both cues. This remains the case even if the signal strength of the z-location change condition is reduced to a quarter of that of the reconstituted cue.

As the level of stereoacuity measurable may change based on fusional load, dynamic stimuli may have been harder for individuals to fuse, thus reducing any difference between static and dynamic stimuli. Chapter five shows that the maintenance of fusion during stereoscopic viewing, including the use of positive relative vergence, does not have a negative impact on stereoacuity thresholds under static of dynamic presentation.

These findings support the reports of depth being more easily perceived in moving 3D scenes, (8,30,31,83) specifically attributable to approaching changes in depth. If binocular disparity is presented below an individual's static stereoacuity level, they will not perceive any depth. However, if the stimulus was to move through depth, depth may be perceived. This could lead to the classification of some individuals as 'stereoblind' based on static test methods, and so may be too conservative; dynamic testing could reveal the ability to detect binocular depth.

Comparison to previous studies on depth detection in moving stimuli

Our results provide quantitative support for the anecdotal evidence that depth "appears of a greater magnitude" in dynamic stereoscopic three-dimensional images than in static images, (8) that is depth is more apparent in dynamic stimuli. Similarly, the time taken to recognise a difference in depth is shorter and accuracy is improved when changes in depth are included in the stimuli. (9) The results presented here add to these findings by isolating the cues to depth & motion in depth, investigating them directly against controls by measuring depth detection thresholds using adaptive procedures.

A previous study investigated the association between the amount of time taken to identify differences in disparity on a moving target and stereoacuity measured using TNO/Titmus test, but no correlation was found between the two variables. (10) Whilst this null result was most likely due to methodology (the actual task was to identify a relatively small static relative disparity whilst approaching the subject) rather than there being no difference between static and dynamic stimuli, the results presented here clearly demonstrate that a smaller amount of retinal disparity is required to see depth, when a target approaches, countering any ambiguity caused by the afore mentioned study.

Methodology

The following discussed a number of potential confounds that may occur in methodology.

Lateral Motion

Lateral motion was added to the distractors in each of the 4AFC tasks, in order to prevent the monocular identification of the target patch (one eye viewing of a half image would present as lateral motion). This may result in the inverse of this problem, as it is possible that no lateral motion would be perceived in the stimuli including depth. As complete control of all aspects of stereoscopic motion in depth stimuli is an intractable task, I have attempted to balance the stimuli by controlling the most crucial aspects. When a stimulus translates directly towards the observer in depth, its right and left eye half-images drift with opposite horizontal directional components on each retina. As such, consideration of the presence of motion either on the left or the right retina would reveal which stimulus is moving in depth. Even during binocular fusion by highly stereo-able observers, a degree of lateral motion is frequently perceived, as noted during the pilot stage of the experiment. This has been noted in the stereoscopic literature by Cumming & Parker, (6) who added lateral motion (x-motion) to the “distractor” to prevent responding on the basis of monocular retinal motion alone. Similar considerations, controlling for the influence of monocular motion, have been included in stereomotion studies following Cumming & Parker’s seminal study (3,84). If lateral motion had not been added to the distractor stimuli, the subject’s task would have been made trivially easy, in that they would simply be required to select the stimulus that appeared to contain any form of motion.

Lateral motion could have been added to the target, as well as the distractors in varying ways. If lateral motion was added to the distractors and target however, there would still be a greater amount of lateral motion in the target stimuli. If a random amount of lateral motion were added to the distractors and target, it would introduce a random trajectory for motion in depth. If a random amount were added to the distractors, but a constant amount to the target, the speed of lateral translation would be different in the target also, again providing a method of identifying the target by artifactual means. Additionally, and perhaps most importantly, adding any lateral motion to the target would prevent the research question from being answered; it would produce an oblique trajectory with both z and x motion, preventing the isolation of z-location change.

On balance, the approach adopted offered the best stimulus control while allowing the research question to be addressed. Also, as conditions were interleaved (other than in the first experiment (chapter three), where findings were similar to the main experiment (chapter four)), it is unlikely that the subjects learnt to identify the target through lack of lateral motion, ignoring any implied lateral motion and z-location change in this condition only, while continuing to identify the nearest stimulus in all five other conditions. The task was not possible under monocular viewing, and viewed binocularly it would seem unlikely that the change in z-location was not the identifying feature. Regarding chapter three, some element of learning may be evident in the constant stimulus pattern conditions, as the worsening of depth detection threshold caused by changing stimulus pattern is significant in the first experiment. As mentioned, the potential confound of using lateral motion, which may have been more apparent with a constant stimulus pattern did not impact on the main findings in either experiment, any learning effect demonstrated in the first experiment was clearly negated by the interleaving of the conditions in the second experiment (chapter 4).

The Control Stimulus in Chapter four

The control stimulus, an isolation of the IOVD cue, contained no coherent disparity signal over time – suggesting that the subjects would be unable to perform the task of identifying depth, and if they provided an answer it would be based on discriminating receding from approaching stereomotion rather than depth. This stimulus contained cues that were also available in some of the experimental stimulus, but that were judged as being unlikely to substantially influence performance. As such, observers were not expected to be able to perform this task, and this hypothesis was confirmed by the universally poor performance of observers: in other words, the observers did not make use of this cue.

One way that the stimulus that is closest in depth could have been identified is through the binocular matching of second-order (or "texture defined") features; the defined edges. (85-87) Although the benefit of this was considered unlikely, effective use of this cue would be revealed by good performance in the control condition of chapter four. Furthermore, observers in conditions four or five may have simply selected the stimulus that was moving in depth (perhaps using the IOVD cue to stereomotion), hence answering the question of which stimulus appeared closer without actually processing any disparity information per se.

It is important also to consider that in the control condition, the relative motion of the target compared to distractors is effectively doubled, given that motion of the distractors was equal and opposite to the motion of the target patch. This was in acknowledgement of early work specifying that the IOVD cue is most effective in simulating motion in depth when contrasting, or relative motion is present. (53) Here, an additional opportunity for high performance in this task is being offered, which might cast doubt on responding in other conditions that included a motion in depth percept. However, as previously stated performance was poor in this condition, even for the small minority of participants for whom reliable curve fits were possible (12 of 127 subjects included in chapter four). Hence, it seems that participants were unable to make use either of second-order disparity signals, or motion in depth signals provided by the IOVD cue in this condition, it is equally unlikely that these cues contaminated responses in the other experimental conditions.

Implied shape as a potential cue

While the dot elements which defined the individual cues were not evenly distributed within the patch, they conformed to the same boundary, and this "second order" boundary may have implied both temporal and spatial correlation between the eyes. If this cue was used to perform the task, it should have been more marked in the conditions containing a change in pattern. This, however, was not the case. Conditions with changing patterns had on average a higher threshold than the non-changing pattern versions. As discussed above, the performance for the control stimuli containing only IOVD (chapter 4), did not benefit from any implied spatial correlation. Further evidence against this is provided in chapter six, where the 'reconstitution' of the changing disparity and velocity difference cues provided significantly higher depth detection thresholds than stimuli patches with a quarter of the signal dots (but each dot contained both cues).

Signal doubling and cross talk

As mentioned in the above section, the stimuli in the control condition were 'doubled': the half images of the target were crossed (motion out of the screen), and the distractors were uncrossed (motion into the screen). This was not the case in all other conditions in the thesis. Arguably cross talk between the right and left half images of the target stimuli may have provided the 'answer' through double images, which would be exacerbated by the provision of subject feedback.

Uncrossed disparity was not used in the distractor images to avoid doubling the signal, and to allow smaller jumps in the level of disparity levels presented (e.g. 18" non-doubled vs 36" with doubled stimuli) without employing anti-aliasing. Any benefit of crosstalk would have impacted on each condition equally and findings suggest that cross talk was not used by the observers for any task. In the context of binocular viewing, ghosting was not detectable during the design stage, and was not mentioned during debriefing by any of the participants.

As mentioned in the general methods section cross talk was measured. For example, in the experiment in chapter four, the luminance of the right eye stimulus through the right filter was 27 cd/m2 whereas the luminance of the right eye stimulus through the left filter was 1.5 cd/m2. Black Level was 0.29 cd/m2. Using the optical cross talk equation (20) the percentage of cross talk was 4.5%.

$$C = \frac{L_G - L_{BL}}{L_M - L_{BL}} \times 100$$

Where L_M = Luminance of main image, L_G = Luminance of crosstalk image, L_{BL} = LCD background luminance.

Whilst the effect of crosstalk might vary with disparity (perhaps more obvious in larger disparity trials) the effect would be similar across conditions. If the signal generated by the crosstalk was utilized, all subjects could achieve at least the largest disparity. Through the use of a chin/forehead rest, the eyes were aligned with the center of the screen to minimize cross talk, and control the confound.

Subjects were unable to make use of this to provide reliable thresholds, and even if employed to some extent, the effect would be consistent across conditions.

Choice of adaptive procedure and threshold estimation

The detection threshold was not the disparity converged on by the adaptive procedure during the experiment; instead it was calculated by fitting a psychometric curve after the experiment was completed. The average number of trials was for each condition in every experiment was between 50 and 150, which is an appropriate number for threshold estimation. (88) To use an adaptive procedure for stimulus placement, but not for the estimation of the final threshold estimation is also common, with the advantage that by fitting the psychometric function 'off-line', data across different sessions can be combined and goodness-of-fit can be evaluated. (89)

As a check, the threshold values that the staircases converged on were compared to those estimated from the fitted Weibull functions. The average, of the average of the last four reversals for each staircase (starting at 10 and 20 pixel disparity) in each condition were calculated (Table 7.1). The average difference between the threshold estimated by the Weibull function and averaging thresholds was on average 20" (7") (mean(SD)) higher using the Weibull method, however, this difference was only statistically significant in the IOVD/CONTROL condition when Bonferroni corrections were made, showing that our results are robust.

Table 7.1: Table demonstrating the thresholds yielded via last four reversals and Weibull using data from chapter four, including all subjects.

			Paired Differences			t	df	Sig. (2-tailed)
	Mean Threshold		Mean	SD	SEM			
	Last Four	Weibull						
STATIC	385.4002	397.26677	-11.8666	100.3373	8.83421	-1.343	128	0.182
STATIC PC	367.7558	389.53557	-21.7798	112.6207	9.9157	-2.196	128	0.03
CDOT	331.7888	354.73523	-22.9465	115.5509	10.17369	-2.255	128	0.026
IOVD	503.6667	532.26068	-28.594	88.97107	7.83347	-3.65	128	0
Combined	294.4467	306.20338	-11.7567	114.9997	10.12516	-1.161	128	0.248
X-Motion	380.4661	402.89886	-22.4328	102.9892	9.06769	-2.474	128	0.015

$\alpha = 0.008$ for significance – Only IOVD (CONTROL) condition is statistically significantly different between threshold estimation methods

Subject filtering

We recruited a very large sample of observers and obtained a large variation in performance across observers. A significant proportion of observers were not able to perform the tasks. We therefore developed a criterion to decide which observers to include in the analysis. An arbitrary criteria of $r^2>0.3$ was used to determine a poor fit in all experiments and could have resulted in the disregarding of poor performance that was not due to chance. To address this issue a simulation of 1000 subjects making a decision on the closest target at random was created, and the Weibull function was fitted to these data using the largest experiment (chapter four) as a basis. None of the simulations resulted in a staircase that converged; the simulation was ended when the IOVD staircase reached a maximum of 150 trials. The staircases all reached the ceiling value of 543 for every condition. Upon fitting the Weibull function to this data, the goodness of fit (r^2) were all negative (the model fit is worse than assuming a constant).

As it were not possible for a staircase to converge by chance, our filtering criteria may have been overly conservative. The analysis was repeated again using $r^2 = 0$ as a cut off. The results are shown in table 7.2, where a higher percentage of reliable fits is shown (any non-negative), 20 subjects were still unable to show a reliable fit in any condition.

Table7.2: Data from chapter four including subject data points with a reliable threshold ($r^2>0$) in at least one condition.

N=109 (of 129)	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
% Satisfactory Fit (n)	81% (105)	81% (104)	74% (96)	84% (109)	80% (103)	44% (57*)
Threshold	321	307	255	236	236	336
SEM	23	23	24	35	21	22

*as with previous analysis only three subjects provided a threshold below ceiling in the control (IOVD) condition

The two way ANOVA analysis showed an identical pattern to that found previously. With an r2 = 0 cut off, of the 109 subjects, 47 were able to provide a reliable threshold in each condition included in this analysis. Data are represented in figure 7.1. Here, thresholds were lower for conditions involving changing depth: an observation that was confirmed by the presence of a statistically significant main effect of Depth ($F(1,184)=13.68$, $p<0.001$). No main effect of Pattern was found, as indicated by the similar thresholds for the two plots ($p=0.778$). The interaction between Pattern and Depth was not significant ($p=0.533$), indicating that the enhancements brought by changing depth apply equally to all stimuli regardless of the persistence of the pattern.

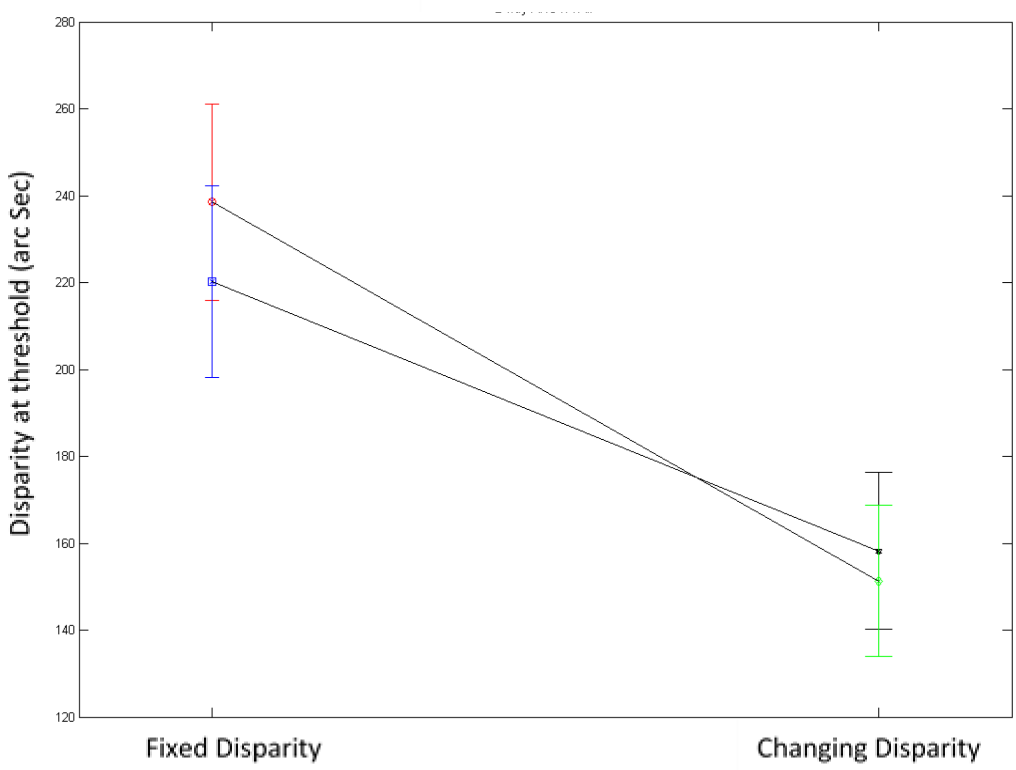


Figure 7.1: Factorial combination of the Disparity and Pattern factors for n=47 subjects with cut off criteria of r2=0.0. Error bars represent ±1SEM, the line joining the red and green bars signifies the changing pattern conditions.

High disparity discrimination thresholds in all experimental conditions

With stereoacuity thresholds measurable down to two seconds of arc, the thresholds recorded in all chapter/experiments in this thesis may seem poor.

Here are some reasons that might explain this discrepancy.

1. Screening thresholds (Fly test) and thresholds measured in the experiment closest to the screening test (e.g. static condition) were derived from different tasks with different parameters (e.g. display time) and it would not expected that these thresholds agree with each other. Whilst the 4AFC is, in principle, a good paradigm for measuring performance with naïve observers,

the task in all experiments was more difficult than the simple Fly test, and therefore observers that pass the fly test would not necessarily produce reliable thresholds in the experimental conditions. Other differences such as eccentricity, display time, and spatial parameters may also contribute and are discussed below.

2. The aim was not to measure the limiting stereoacuity performance, but allow conditions to be comparable without floor or ceiling effects.
3. Display time in the experiments were limited to one second, whereas the fly test has no time restriction.
4. Disparity thresholds depend on spatial frequency, with peak stereoacuity (3-4 arc sec) found at 0.3 cpd when sinusoids are used. (49) The experimental stimuli used here are more broadband (in frequency space) and shifted to higher spatial frequencies, well beyond the optimal spatial frequency for stereoacuity.
5. Stereoscopic discrimination thresholds increase as eccentricity increases. Rawlings and Shipley (1969) demonstrated that from an average threshold of 25", introducing an eccentricity from fixation to target of 4^{o} increased threshold to 150". (50) The inner corners of each of the four stimuli were initially separated from the centre of the fixation target horizontally by 0.6^{o} (120 pixels) and vertically by 0.68^{o} (135 pixels). Similar dependency on eccentricity has been reported for different spatial frequencies (0.5 to 8cpd). (51) As for display time and spatial frequency, our stimuli were not optimised to measure limiting stereo-acuity performance, but rather compare static and dynamic conditions.

The results in this thesis demonstrate a large variability for stereovision, and hence the need for a large sample to address any research question relating to it. The aim was to obtain a representative estimate of the population performance.

Cue conflict

One theoretical comment that could be addressed is the increased (or at least different) cue conflict introduced by the stereomotion stimuli. In all the experiments there was a monocular cue conflict and this could contribute to insensitivity of the stereotests. As the target approaches, it would be expected to increase in size. As with the vast majority of experiments, the binocular display used here contains a depth cue conflict which is often a consequence of isolating a particular cue. In these experiments, the conflict between the monocular and binocular cues are present in all conditions and so is unlikely to have had an impact on the results.

Clinical Implications and future plans

Returning to the premise that approaching motion could be responsible for the compelling perception of volumetric depth described in the introduction to this thesis, the evidence here arguably support this theory. It could be claimed however, that there is no direct relationship between how 'compelling' depth is and depth perception at threshold, and so these findings may not predict how "compelling" depth appears to an observer based on stereo discrimination thresholds. It can be assumed however, that whilst subthreshold stimulus attributes may not contribute to conscious perception, supra-threshold attributes do. Lower thresholds hence imply a larger range of stimuli will appear to have stereoscopic depth, while higher thresholds imply the opposite.

These experiments have shown that individuals with demonstrable stereoacuity using standard clinical testing, demonstrate lower thresholds when the stimuli contain changes in disparity. The next step will be to carry this forward into a clinically deliverable test, to assess individuals without readily demonstrable stereoacuity using static methods. The limitation of current clinical test methods as mentioned previously, are the limited range and large steps between threshold levels tested. With depth more apparent using dynamic stimuli, smaller disparities may be needed for individuals to appreciate depth. Combined with digital presentation methods to allow dynamic presentation, the incorporation of automatic staircase procedures would also provide a far superior assessment of stereoacuity.

Standard testing to assess binocular potential prior to surgical management often includes a correction of any angle of deviation and assessment of binocular function. (90) As shown in chapter five, as long as comfortable fusion is achieved, thresholds are not significantly different to those achieved when orthophoria is achieved, therefore this alignment should offer a good indication of any binocular potential. Binocularity is not always readily demonstrated however, potentially as only a limited number of binocular processing areas are stimulated, or as binocularity is actively suppressed to prevent diplopia.

Neurophysical evidence has demonstrated that neurones in V1 do not directly account for many perceptual features, with neurophysical evidence showing that neurones in the striate cortex are tuned to static disparities, and are insensitive to disparity changes over time. (91) The neurones in the primary visual cortex appear to use static disparities only to solve the correspondence problem. (92) This further supports the notion that the detection of depth within stereomotion stimuli occurs in areas beyond the primary visual cortex. Whilst the work by Nienborg et al. suggests an insensitivity to stereomotion, low spatial frequency stimuli were used in their experiment. The stimuli used in this thesis are not sinusoidal gratings, but checkerboard stimuli with a fairly broad spatio-temporal frequency spectrum. A direct comparison with simple spatial (or temporal) sinusoidal stimuli is not straightforward. . Similarly, Kane et al. show that individuals are better at detection disparity at lower temporal frequencies, (93) contrary to our findings. Again however, our stimuli was not of a single frequency, and even our static stimuli had a sharp on and off-set, which make our findings difficult to compare.

The processing of static disparity occurs in a number of other visual areas as shown by fMRI scanning: V1, V2 and V3 provide small responses to absolute and relative disparity, V3A, MT and V7 respond more markedly to absolute disparity and V4 and V8 respond equally to both. (94) Whilst all these areas would respond to the disparity in standard clinical tests, a further area anterior to MT has been shown to respond to motion through depth specifically. (95-97) Assessment of binocular potential using dynamic stimuli may offer extra opportunities for the visual system to demonstrate binocular potential.

Whilst the motion centre, MT, was previously considered a static disparity processing area, (96) that processes structure from motion. (98) Electrophysiological results in Macaques provided evidence that neurones in MT are in fact tuned for motion through depth, distinct from tuning to binocular disparity. (97) By assessing the ability of an individual to detect frontoparallel motion, and therefore recognise depth, all areas of binocular processing are assessed, proving a more complete assessment of binocular potential, in turn guiding the functional correction of strabismus.

Correction of an angle of deviation on its own arguably has little effect of countering any interocular suppression present. The process of preventing binocular responsiveness is an active one, (99) that can be reversed pharmacologically, (100) or by restoring contrast summation through attenuating signal strength to the non-amblyopic eye. (101) This suggests that in order to fully investigate any binocular potential the signals to both eyes should be balanced to account for any suppression present, be that facultative to prevent diplopia or amblyopia.

This feeds into two different applications where the investigation or intervention could be delivered by a similar methodology, namely the treatment of amblyopia and the investigation of binocular potential thought the use of a dichoptic display. As technology progresses and becomes more mainstream the cost of the consumer items reduce. The paradigm of domestic stereoscopic displays have shifted from 3D televisual devices towards virtual reality headsets. These offer a presentation similar to the synoptophore / wheatstone stereoscope in that two separate images are displayed to each eye individually, with zero risk of cross talk.

Whilst binocular balancing has been approached through augmentation of contrast, (101-103) the deficit to vision in amblyopia is not limited to just contrast, the perceived 'structure' of the image is impaired, (104) formalised as a reduction in optotype, grating and Vernier acuity. (105) All of these visual deficits could be simulated using virtual reality headsets. This offers an evolution from the use of total occlusion, form occlusion, neutral density filters and reducing luminance to degrade the signal to the dominant eye, allowing binocular treatment and assessment.

Conclusion

Approaching motion, motion in depth, motion through depth or z-location changes are interchangeably used to describe variations along the z-axis of a moving stimulus. These changes allow for depth to be perceived at smaller thresholds than static disparity displays alone. This suggests that the systems for detecting changes in disparity can make use of extra information beyond the systems that detect static disparity. This is unsurprising, as in real life, disparity is rarely static, and the information we gain from binocular processing is used to navigate and survive interactions in the real world. By only assessing static disparity, we do not fully assess the binocular abilities of an individual. Binocular vision must be assessed and treated in more depth.

Appendices

Appendix I – Ethical Approval

From: IPHS Ethics
Sent: 09 April 2013 11:17
To: Wuerger, Sophie
Subject: IPHS-1213-LB-064-Stereoscopic vision research including clinical assessment of visual function

Dear Sophie

I am pleased to inform you that IPHS Research Ethics Committee has approved your application for ethical approval. Details and conditions of the approval can be found below.

Ref: IPHS-1213-LB-064
PI / Supervisor: Sophie Wuerger
Title: Stereoscopic vision research including clinical assessment of visual function
First Reviewer: Laurence Alison
Second Reviewer: Ian Donald
Third Reviewer (if applicable): N/A
Date of Approval: 09.04.13

The application was APPROVED subject to the following conditions:

Conditions

1 All serious adverse events must be reported to the Sub-Committee within 24 hours of their occurrence, via the Research Governance Officer (ethics@liv.ac.uk).

2 This approval applies for the duration of the research. If it is proposed to extend the duration of the study as specified in the application form, IPHS REC should be notified as follows. If it is proposed to make an amendment to the research, you should notify IPHS REC by following the Notice of Amendment procedure outlined at http://www.liv.ac.uk/researchethics/amendment%20procedure%209-08.doc.

3 If the named PI / Supervisor leaves the employment of the University during the course of this approval, the approval will lapse. Therefore please contact the Institute's Research Ethics Office at iphsrec@liverpool.ac.uk in order to notify them of a change in PI / Supervisor.

Best Wishes
John Downes
Chair, Ethics Committee

Appendix II – Planar System example

PLANAR

The Gold Standard in Stereoscopic Displays

- High Resolution Stereo Image
- Flicker-free Comfort
- Easy to Setup. Easy to Use

FEATURES:

- Multiple resolutions and sizes
- Full-resolution stereo viewing
- Flicker-free, high-contrast imaging
- Viewable in typical office lighting
- Multi-user, wide-angle viewing
- Side monitor option available
- Compatible with numerous off-the-shelf graphics cards
- Plug-and-play with OpenGL and DirectX applications that support stereo
- Includes 5 pair of passive polarized glasses
- Readily converts from stereo/3D to standard 2D
- 1-Year Customer First™ Warranty

Find out everything that can be accomplished with a truly versatile stereoscopic display.

3D/Stereoscopic Monitors

Planar's SD product line, featuring innovative StereoMirror™ technology, provides the highest quality stereoscopic image available in desktop monitor. These displays have the exemplary resolution and brightness you've come to expect from Planar. StereoMirror technology delivers stunning images for use in applications such as:

- Geospatial & Photogrammetry
- Medical Imaging
- Molecular Modeling
- Data Visualization
- Oil & Gas Exploration
- Mechanical Design
- 3D Post Production
- Simulation & Training

Planar's SD line is available in four sizes: a 17" with 1280x1024 resolution, an HD 22" with 1920x1080 resolution and both a 24" and 26" model boasting 1920x1200 wide-format resolution. Planar StereoMirror monitors deliver the full resolution to both eyes without compromising contrast, color or image quality you're used to seeing on a 2D monitor.

StereoMirror technology enables an unprecedented level of stereo viewing comfort. Flicker-free operation allows extended stereo use with no discomfort. The monitor provides ample brightness to be used in normal office lighting. Passive glasses allow multiple users to view superb stereo from a wide range of viewing positions.

www.Planar3d.com

Appendix III – Stimuli Patch Generation Script

Example script used for the main experiment to create the CHANGING DEPTH conditions

```
close all;
clear all;

width = 10;
height = 10;
percentageWhite = 0.75; % between 0 and 1



for n=1:60

   % Seed the random number generator
   r=rand(height,width,'double');


   G=find(r<percentageWhite);
   B=find(r>percentageWhite);

   r(G)=0.5;
   r(B)=0;

   dotPattern=r
   for i=1:width
      for j=1:height
         if (dotPattern(i,j)==0)
            dotPattern(i,j);
         end
      end
   end

   imagesc(dotPattern);
   colormap('gray');
   axis equal;
   imagename=strcat(int2str(n),'.png');
   imwrite(dotPattern, imagename,'png');
%     dotPattern = reshape(dotPattern(randperm(numel(dotPattern))), height,
width);
end
```

The following was used the create the CONTROL condition (different dots to the right and left eye) and the CHANGING DEPTH & CHANGING PATTERN condition (including varying percentages of each from chapter 6 experiments, and an example of unique presentations)

```
close all;
clear all;

width = 10;
height = 10;
percentageWhite = 0.75; % between 0 and 1
stimPer=[0.04,0.08,0.16,0.24,0.32,0.40,0.48]%between 0 and 1

for set=7
    percentWanted = stimPer(set)




    for n=0:60

        r=rand(height,width,'double');


        G=find(r<percentageWhite);
        Bl=find(r>percentageWhite);

        r(G)=0.5;
        r(Bl)=0;

        while length(Bl)~=25
            r=rand(height,width,'double');
            G=find(r<percentageWhite);
            Bl=find(r>percentageWhite);

            r(G)=0.5;
            r(Bl)=0;
        end

        dots=r;
        [row,col]=find(dots==0);


        k=numel(row);%how many elements have been randomly selected to be black
- should be 25 but, it is random
```

```
    kh=round(percentWanted*k);%the percent wanted for each thing . .
%     k=round(0.5*numel(B));
    sample=datasample([row,col],k,'Replace', false);
%     R=datasample([row,col],k,'Replace', false);

    L=sample(1:kh,:);
    R=sample(kh+1:kh*2,:);
    dP=sample(kh*2+1:end,:);


    mL=ones(width,height).*0.5;
    mR=ones(width,height).*0.5;
    A=ones(width,height).*0.5;
    B=ones(width,height)*0.5;
    C=ones(width,height)*0.5;
    D=ones(width,height)*0.5;


    for i=1:kh;
        mL(L(i,1),L(i,2))=0;%in L the first rows up to kh contain the necessary
instructions as to which vector to 'colour'
        mR(R(i,1),R(i,2))=0;%in R the first kh rows are blank so we need to take from
further (i.e. kh to kh*2)

    end




    num2shuf=length(dP(1)); %Something Strage here - in the 48% dp has to be
manually set to one - otherwise we get two, works ok for others though - in this
situation there is only a vector with two elements, its counts them rather than
counting rows as in the others)the dot pattern has the numebr of elements we
need to re jig
    [rowAvail,colAvail]=find(dots==0.5);

    dPLen=num2shuf*3;
    list=randperm(1*dPLen);

    sampleB=[rowAvail(list(1:num2shuf)),colAvail(list(1:num2shuf))];

sampleC=[rowAvail(list(num2shuf+1:num2shuf*2)),colAvail(list(num2shuf+1:num2s
huf*2))];

sampleD=[rowAvail(list(num2shuf*2+1:num2shuf*3)),colAvail(list(num2shuf*2+1:n
um2shuf*3))];
```

```
	for i=1:num2shuf;
	   A(dP(i,1),dP(i,2))=0;
	   B(sampleB(i,1),sampleB(i,2))=0;
	   C(sampleC(i,1),sampleC(i,2))=0;
	   D(sampleD(i,1),sampleD(i,2))=0;
	end %this is to allow the remainer of the points to be displayed - the both
condition e.g. the CHANGING DEPTH & CHANGING PATTERN CONDITION,

	mL=imresize(mL,10, 'nearest');
	mR=imresize(mR,10,'nearest');
	A=imresize(A,10,'nearest');
	B=imresize(B,10,'nearest');
	C=imresize(C,10,'nearest');
	D=imresize(D,10,'nearest');



	alphaSet=0;%this is the level of transparency - 0 being 100% trans and 1 being
0% transparent!
	Set=0.5;%this is to define which part i want to make transparent


	indalphamL=find(mL==Set);%to set transparency channel
	matalphamL=ones(size(mL));
	matalphamL(indalphamL)=alphaSet;

	indalphamR=find(mR==Set);%to set transparency channel
	matalphamR=ones(size(mR));
	matalphamR(indalphamR)=alphaSet;

	indalpha=find(A==Set);%to set transparency channel
	matalpha=ones(size(A));
	matalpha(indalpha)=alphaSet;

	indalphb=find(B==Set);%to set transparency channel
	matalphb=ones(size(B));
	matalphb(indalphb)=alphaSet;

	indalphc=find(C==Set);%to set transparency channel
	matalphc=ones(size(C));
	matalphc(indalphc)=alphaSet;

	indalphd=find(D==Set);%to set transparency channel
	matalphd=ones(size(D));
```

```
    matalphd(indalphd)=alphaSet;



    imagesc(mL);
    imagesc(mR);
    imagesc(A);
    imagesc(B);
    imagesc(C);
    imagesc(D);



    colormap('gray');
    axis equal;

    fldr=percentWanted*100;
    %fldr required the folders to exsist in directory - created for each
    %percentage required . . . both20% is actually remainder of points
    imagenamemL=strcat('Left',int2str(fldr),'%/',int2str(n),'L.png');

 %    imwrite(mL, imagenamemL,'png','Alpha',matalphamL);
    imwrite(mL, imagenamemL,'png','Alpha', matalphamL);

    imagenamemR=strcat('Right',int2str(fldr),'%/',int2str(n),'R.png');

 %    imwrite(mR, imagenamemR,'png','Alpha',matalphamR);
    imwrite(mR, imagenamemR,'png','Alpha', matalphamR);



    imagenamemA=strcat('Both',int2str(fldr),'%/',int2str(n),'a','.png');
    imwrite(A, imagenamemA,'png','Alpha', matalpha);

    imagenamemB=strcat('Both',int2str(fldr),'%/',int2str(n),'b','.png');
    imwrite(B, imagenamemB,'png','Alpha', matalphb);

    imagenamemC=strcat('Both',int2str(fldr),'%/',int2str(n),'c','.png');
    imwrite(C, imagenamemC,'png','Alpha', matalphc);

    imagenamemD=strcat('Both',int2str(fldr),'%/',int2str(n),'d','.png');
    imwrite(D, imagenamemD,'png','Alpha', matalphd);

  end
end
```

Appendix IV – Chapter four additional data

A table to show the conditions where a reliable threshold was achieved by each subject (defined as an r^2 of at least 0.3):

	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
1	No	No	No	No	No	No
2	No	No	No	Yes	No	No
3	No	No	No	No	Yes	No
4	No	No	No	Yes	No	No
5	No	No	No	No	No	No
6	No	No	Yes	Yes	Yes	No
7	No	No	No	Yes	No	No
8	No	No	Yes	No	No	No
9	No	No	Yes	No	Yes	No
10	No	No	No	No	No	No
11	Yes	Yes	Yes	Yes	Yes	No
12	Yes	No	No	Yes	No	No
13	No	No	No	Yes	No	No
14	No	No	No	No	No	No
15	No	No	No	No	No	No
16	No	No	No	Yes	No	No
17	No	No	No	Yes	No	No
18	No	No	No	Yes	No	No
19	No	No	No	Yes	No	No
20	No	Yes	No	No	No	No
21	No	No	No	Yes	No	No
22	No	No	Yes	No	No	No
23	No	No	No	Yes	No	No
24	No	No	No	No	No	No
25	No	No	No	Yes	No	No
26	No	No	No	No	No	No
27	No	No	No	No	No	No
28	No	No	No	No	No	No
29	No	No	Yes	No	No	No
30	No	No	No	No	No	No
31	No	No	No	Yes	No	No
32	No	No	No	No	No	No
33	No	No	Yes	No	No	No

Subject ID	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
34	No	No	No	No	No	No
35	No	Yes	No	No	No	No
36	No	No	No	Yes	No	No
37	No	Yes	No	Yes	No	Yes
38	No	No	No	No	No	No
39	No	No	No	Yes	No	No
40	No	No	No	Yes	No	No
41	No	No	No	No	Yes	No
42	Yes	Yes	Yes	Yes	Yes	Yes
43	No	No	No	No	No	No
44	Yes	Yes	No	Yes	No	Yes
45	No	No	No	Yes	No	No
46	Yes	No	Yes	No	No	Yes
47	No	No	No	No	No	Yes
48	No	No	Yes	Yes	Yes	No
49	No	No	No	No	No	No
50	No	No	Yes	No	No	No
51	No	Yes	No	Yes	Yes	No
52	No	No	No	Yes	Yes	No
53	Yes	No	Yes	Yes	No	No
54	No	No	No	Yes	No	No
55	No	No	No	Yes	No	No
56	No	Yes	Yes	Yes	No	Yes
57	No	No	No	No	No	No
58	No	No	No	No	No	No
59	No	No	No	Yes	No	No
60	No	No	No	No	No	No
61	No	No	No	Yes	No	No
62	No	No	No	Yes	No	No
63	Yes	Yes	Yes	Yes	Yes	Yes
64	Yes	Yes	No	No	No	No
65	No	No	No	No	No	No
66	No	Yes	Yes	Yes	No	No
67	Yes	No	Yes	No	No	Yes
68	Yes	Yes	Yes	Yes	Yes	No
69	No	No	No	No	Yes	No
70	No	Yes	No	No	No	No
71	Yes	Yes	No	Yes	Yes	Yes
72	Yes	Yes	No	Yes	Yes	Yes
73	No	No	Yes	Yes	No	No
74	No	No	Yes	Yes	Yes	Yes
75	No	No	No	No	Yes	No

Subject ID	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
76	No	No	No	No	No	No
77	No	No	No	No	Yes	No
78	No	No	No	Yes	No	No
79	Yes	No	Yes	Yes	Yes	No
80	Yes	Yes	Yes	Yes	Yes	No
81	No	No	No	No	No	No
82	No	No	No	No	No	No
83	No	No	No	Yes	No	No
84	No	No	No	No	No	No
85	No	No	No	No	No	No
86	Yes	No	Yes	No	No	No
87	No	No	No	Yes	Yes	No
88	No	No	No	Yes	No	No
89	No	No	No	No	No	No
90	No	No	No	Yes	No	No
91	No	No	No	Yes	No	Yes
92	No	No	No	Yes	Yes	No
93	No	No	No	No	No	No
94	No	No	Yes	Yes	No	No
95	Yes	No	No	Yes	No	No
96	Yes	Yes	Yes	Yes	No	Yes
97	Yes	No	Yes	Yes	No	Yes
98	No	No	No	Yes	No	Yes
99	No	Yes	Yes	Yes	Yes	No
100	Yes	Yes	Yes	Yes	No	Yes
101	No	No	No	Yes	No	No
102	No	No	No	Yes	No	Yes
103	Yes	Yes	Yes	No	Yes	Yes
104	No	No	Yes	Yes	Yes	No
105	No	Yes	No	No	No	No
106	No	No	Yes	No	No	No
107	No	No	No	Yes	No	No
108	No	No	No	Yes	No	No
109	No	No	No	No	No	No
110	No	No	No	Yes	No	Yes
111	No	No	No	No	No	No
112	No	No	No	Yes	No	No
113	No	No	No	No	No	No
114	No	Yes	No	Yes	No	No
115	No	No	No	No	Yes	No
116	No	No	No	No	No	No
117	No	No	No	No	No	No

Subject ID	STATIC	PATTERN CHANGE	Z-LOCATION & PATTERN CHANGE	X-LOCATION CHANGE	Z-LOCATION CHANGE	CONTROL
118	No	Yes	Yes	No	No	No
119	No	No	No	Yes	No	No
120	No	No	No	Yes	No	No
121	Yes	No	No	Yes	No	No
122	No	Yes	Yes	Yes	No	No
123	Yes	No	No	No	No	No
124	Yes	Yes	Yes	Yes	Yes	Yes
125	Yes	No	No	Yes	No	No
126	No	No	No	No	No	No
127	No	No	No	Yes	No	No
128	No	No	No	Yes	No	No
129	No	No	No	Yes	No	No

Appendix V –Sections as published

The sections of the published papers appear in sections, as detailed in bold.

Chapter Three: Tidbury LP, O'Connor AR, Wuerger SM. Dynamic Cues to Binocular Depth. Br Ir Orthopt J 2016;13.

All areas of project carried out by LT, with review and advice from AOC and SW. This paper forms chapter three of the thesis.

Chapter Four: Tidbury LP, Brooks KR, O'Connor AR, Wuerger SM. A systematic comparison of static and dynamic cues for depth perception. Invest Ophthalmol Vis Sci 2016;57(8):3545-3553.

All areas of project carried out by LT, with review and advice from AOC, SW and KB. The paper forms chapter four of the thesis.

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